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Geology and Resource Potential of Phosphates in Alberta and Portions of Southeastern British Columbia

by

ⓒ D.E.Macdonald

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Date November 30, 1984

ABSTRACT

This study outlines the resource potentials of phosphate rock in Alberta and adjacent portions of southeastern British Columbia, primarily for its phosphorous content and secondarily for its associated uranium, vanadium, and rare earth elements.

Phosphate is found in four major geological units in the Cordillera of Alberta and southeastern British Columbia: the Devonian-Mississippian Exshaw Formation; the Permo-Pennsylvanian Rocky Mountain Supergroup; the Triassic Spray River Group, and the Jurassic Fernie Group. Within these four major units, thirty-three stratigraphic zones contain varying amounts of phosphatic material. Only two horizons seem to have any real future potential; at the base of the Permian Ranger Canyon Formation, and at the base of the Jurassic Fernie Group.

The Exshaw Formation has its best phosphate potential in the Crowsnest Pass region of Alberta. Grades of phosphate are up to 25% P_2O_5. However, none of the seams exceed 50 cm in thickness. Mining conditions would be very difficult in the Crowsnest area due to the lack of easily accessible overburden-free outcrops of Exshaw. The maximum in situ resources of the Exshaw are estimated to be less than 10 million t of low grade (6-12% P_2O_5 over at least 1 m) phosphate rock.

The Rocky Mountain Supergroup has its best phosphate potential in the Johnston Canyon Formation (16-99 million t), and at the base of the Ranger Canyon Formation (39-235 million t). These resources are mostly of a low grade (6-12% P_2O_5 over l m). Sixty-nine percent of the available resource areas of these zones are in areas of restricted land use with respect to mining (National or Provincial Parks, or designated "Prime Protection" areas). Of the remaining 31%, 28% of this resource is in the Fernie Basin area of British Columbia.

The Spray River Group has very little phosphate potential, except perhaps two zones in the Whistler Member of the Sulphur Mountain Formation. Details of these zones are sketchy but results thus far suggest limited potential.

The Fernie Group has resources of 29 to 175 million t of 18% or greater P_2O_5 over 1 m, with nearly all of it found in the Fernie Basin area of British Columbia. Lower grade (6-12% P_2O_5 / 1m) phosphate rock is present in Alberta, but does not likely exceed 260 million t, of which only 3% is in unrestricted land use areas.

Uranium contents have a mean value of 34 ppm in the Alberta phosphorites and show a weakly positive linear relationship with phosphorous. The correlation is stronger within certain P_2O_5 ranges (particularly 18-32% P_2O_5) and in certain stratigraphic horizons.

Vanadium content in phosphatic rocks is found to have very little relationship to phosphorous content, with even a slight tendency to be negatively correlated. Vanadium values in phosphorites vary from 46 to 255 ppm, and reach up to 0.4% V in non-phosphatic shales.

Fluorine content averages 4.09% in these phosphorites. Rare earth and trace elements show anomalous concentrations above normally enriched phosphorites, especially in the elements: La, Ce, Nd, Sm, Eu, Tb, Dy, Ho, Tm, Yb, Lu, As, Cd, Mo, Ni, Se, V, Zn and Zr.

The mineralogy of these phosphorites is transitional between pure francolite and pure fluorapatite. Minor amounts of dahllite are also present. A variety of petrographic lithotypes are present and include: pellets - both nucleated, elliptical and structureless; cements - including microsphorite, fluorapatite, and francolite-cementing sandstones, siltstones and conglomerates; intraclasts and pebbles; nodules; and fossil material.

All of the phosphate occurrences were at the time of deposition in a low paleolatitude (<40°N) within the Trade Wind belt, and had shorelines paralleling or nearly paralleling the dominant winds. These conditions, together with the presence of a landmass or submarine rise area in the northern Montana/Idaho area (Montania?), may have contributed significantly to promoting oceanic upwelling. This upwelling, with the resulting flourishing of biota and their subsequent death and decay on the sea floor, is the first step in the phosphate precipitation processes. This causes enrichment of bottom waters several hundred times their normal amounts with respect to phosphorous. Direct authigenic phosphate precipitation or phosphatization within interstitial muds is the final step in the precipitation of these phosphorites. It is believed the Fernie Group pelletal phosphates formed somewhere between the shelf margin to basin position, within a sequence of black shales, cherts and mudstones. The Exshaw Formation, Rocky Mountain Supergroup and Spray River Group phosphorites apparently formed in shallower water shelf positions.

Most of the phosphorites studied are related to worldwide sea level rises throughout the Paleozoic and early Mesozoic, marked by major transgressive events. The remaining occurrences are found at unconformities.

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I. BACKGROUND INFORMATION

A. INTRODUCTION

Phosphate rock is an important industrial mineral commodity in Alberta used primarily in producing agricultural fertilizers. Although phosphate rock is used extensively in the Province, none is mined in Alberta or in Canada. Knowledge of the resource potential for this mineral commodity in Alberta and Western Canada in general would be of vital importance to the long term stability of the agricultural industry. This study outlines the resource potential for phosphate rock in Alberta and southeastern British Columbia as well as addressing some of the more scientific aspects of phosphates.

Objectives

The purpose of this study is two fold:

1. To evaluate the resource potential of phosphate rock in Alberta, primarily as an industrial mineral commodity and secondarily as a possible source of by-product uranium and vanadium. It is hoped that a regional synthesis with respect to phosphates will be of value to industry in providing basic data to guide further exploration and of value to government in policy planning.
2. To provide scientific data, interpretation and synthesis on the petrography, mineralogy, stratigraphy, sedimentology and genesis of phosphates in Alberta.

To these ends the Alberta Geological Survey, in conjunction with the University of Alberta, undertook this study in 1978.

Previous Investigations

Phosphate, as apatite veins and pockets within igneous intrusive rocks, was explored for and produced in Quebec and Ontario during the period from 1829 to 1919 (Spence, 1920). The discovery in the early 1890's of the vast, easily exploitable sedimentary phosphate deposits in Florida undermined the Canadian industry and it slowly collapsed. The search for phosphorous sources shifted to sedimentary phosphate deposits in Western Canada with the discovery by Adams and Dick (1915) of phosphate near Banff in the "Rocky Mountain Park" (Banff National Park). Subsequent investigation of the Banff deposits by de Schmid (1916) concluded that the phosphate beds were of insufficent grade and thickness to be economically exploited, when compared to the thick, high grade deposits known in Montana. Leo Telfer in 1925 conducted an extensive phosphate exploration program in the Rocky Mountains in Alberta for Consolidated Mining and Smelting Company (Cominco), a summary of which was presented to the Canadian Institute of Mining and Metallurgy (Telfer, 1933). Telfer's general conclusions were that phosphate is present in four distinct stratigraphic zones, but was of low grade with an undetermined commercial value. During the period 1925 to 1975 Cominco held several phosphate leases in southeastern British Columbia and in the Crowsnest Pass area of Alberta.

Adits were constructed by Cominco, prior to 1960 at the Crow, Lizard and Corban mine sites in British Columbia to test the metallurgical properties of phosphate found in the lower Fernie Group. None of these sites went into commercial production.

In the 1960's renewed interest in phosphates saw another surge of exploration in Alberta and British Columbia by Cominco, Western Warner Oil, Hudson Bay Oil and Gas, and Mobil Oil. In the period 1972-74 the world price of phosphate nearly tripled, causing another wave of exploration activity by Cominco, Esso, and First Nuclear Corporation. This recent activity was centered in the southeastern Fernie Basin and northeastern areas of British Columbia.

These dramatic price increases in the early 1970's, coupled with the fact that Canada was, and still is, solely dependent on imported phosphate, prompted the federal government to produce a "Canadian Mineral Policy" with respect to phosphates in 1976. In part, this policy stated that with respect to adequate future supplies of phosphate rock in Canada ....

> "The discovery and development of domestic resources should be the prime consideration. In this respect, federal and provincial agencies should provide support by providing increased geological and geophysical data to assist exploration and by providing research to develop means to beneficiate known low-grade ores."

(Energy, Mines and Resources, 1976).

In response to this policy statement the Geological Survey of Canada instigated a country-wide phosphate resource evaluation program. Shortly thereafter (1978) the Alberta Geological Survey initiated this study to assess the provincial potential for phosphate rock.

Field Procedures

After compiling all known occurrences of phosphate from published literature and from publicly available exploration permit reports, a field program was set up to fill in gaps and verify existing data. Particular attention was paid to obtaining good quantitative data regarding grade and thickness, and establishing the stratigraphic and sedimentological setting of each phosphate occurrence. All known phosphate-bearing formations in the Rocky Mountains of Alberta and southeastern British Columbia were examined, regardless of their land zone location and political status, in an attempt to obtain a geometrically equidistant spacing of data points.

Field procedures consisted of measuring, describing and sampling all accessible stratigraphic sections of formations known to be phosphate-bearing. A gamma ray spectrometer was used to assist in detecting phosphate beds based on a known affinity between uranium and phosphates (see Part II, B).

Laboratory Procedures

All samples collected in the field were split in two, with one half kept for visual examination and one half pulverized for chemical analysis. This pulverized portion was further split into two representative halves, one being analyzed for phosphorous and vanadium content and the other for uranium. Uranium was analyzed by Neutron Activation by Atomic Energy of Canada Limited. Detection limits of 0.1 ppm for a l gram sample and a precision limit of about ± 1% are claimed by AECL. Eight replicate samples submitted to AECL yielded a precision of ±5% within the 4-10 ppm range. Phosphorous and vanadium were determined at the Alberta Research Council laboratories using standard wet chemical methods. The same eight replicate samples revealed a precision here of about ± 13% for phosphorous and ± 11% for vanadium of the amount detected.

Standard petrographic thin sections were prepared and examined for all samples containing significant proportions of phosphate. A small portion of these samples was examined using a scanning electron microscope.

Twenty-one samples from all of the stratigraphic units where phosphogenesis occurred, all of the major phosphate petrographic and mineralogical forms, and a variety of geographic positions were selected for study with the electron microprobe.[1] This same group of twenty-one samples was also used for standard mineral identification and apatite CO_2 content by x-ray diffraction.

Four composite samples representing the four major phosphogenic stratigraphic units were sent to Becquerel Laboratories for trace and REE determinations. Each sample was prepared by combining equal portions of 6 to 12, depending on availability, individual samples. Trace and REE determinations were performed by Neutron Activation - Gamma Ray counting techniques.

All stratigraphic and chemical analysis data from all sections were entered into a computer data base management system termed "Datatrieve" (Digital Corporation). Contoured maps were made using the University of Kansas program "Surface II" and statistics were derived using the University of Michigan derived program "Midas". These programs were run on the University of Alberta's Amdahl 470, and the Alberta Research Council's VAX 11/780 mainframe computers.

Land Ownership and Mineral Rights in Alberta

Most of the phosphate-bearing geological units in Alberta are exposed in the Foothills and Front Ranges of the Rocky Mountains. Many of the best exposures are found in Jasper and Banff National Parks, as well as Kananaskis Provincial Park, where no mineral exploration or development is allowed. In 1977 the Alberta Government developed a policy for resource management in all other non-park areas of the Alberta Rocky Mountains (Alberta Energy and Natural Resources, 1977). Several classes of land use have been established, and those that do not permit any mineral exploration or mineral development are shown on Figure 1. In comparing this figure to any of the figures that show the distribution of phosphate-bearing strata (e.g. Fig. 8, 14 or 20) it can be seen that nearly all of the potentially exploitable phosphate horizons fall within this "no mineral development" area.

---

[1] The operating conditions for all probe runs were as follows: Fluorine analyzed by Wave Length Dispersive technique utilizing a TAP3 crystal-detecting Fluorine K alpha wavelength. Peak position for Fluorine set at 18.31999A. All other elements by Energy Dispersive analysis. Operating voltage=15 Kev, Aperture Current=260 nanoamps, Probe Current=26 nanoamps. Beam was kept in constant motion over chosen apatite sample to avoid burning of Fluorine and CO_2. Data was processed using computer program "EDATA II" (Smith et. al., 1979)

Mineral rights on Crown lands are granted by the Province of Alberta and a "royalty" must be paid for any commodity extracted. Phosphate rock falls into this category. "Surface rights" are held by the land owner and include many industrial minerals such as sand and gravel, clay, peat and marl.

Quartz mineral exploration permits are applied for through Alberta Energy and Natural Resources. If they fall within this "no mineral development" area they are at the present time automatically rejected. However, application can be made to Alberta Energy and Natural Resources to have a specified area reclassified under this resource management policy to allow exploration. Resource companies do operate fairly extensively within the Rocky Mountain region of Alberta (limestone and shale quarries, coal mines, etc.), so while there does appear to be a very restrictive environment for mineral development, exceptions are made.

Terms and Definitions

There are many conflicting usages of terms in describing phosphatic rocks. Within this report the following terms and corresponding definitions have been adopted:

Phosphorous - The chemical element (P)

Phosphate - Chemically precipitated minerals of the apatite family, usually carbonate fluorapatite.

Phosphorite - A rock type composed predominantly of carbonate-flourapatite minerals
- a lithologic term.

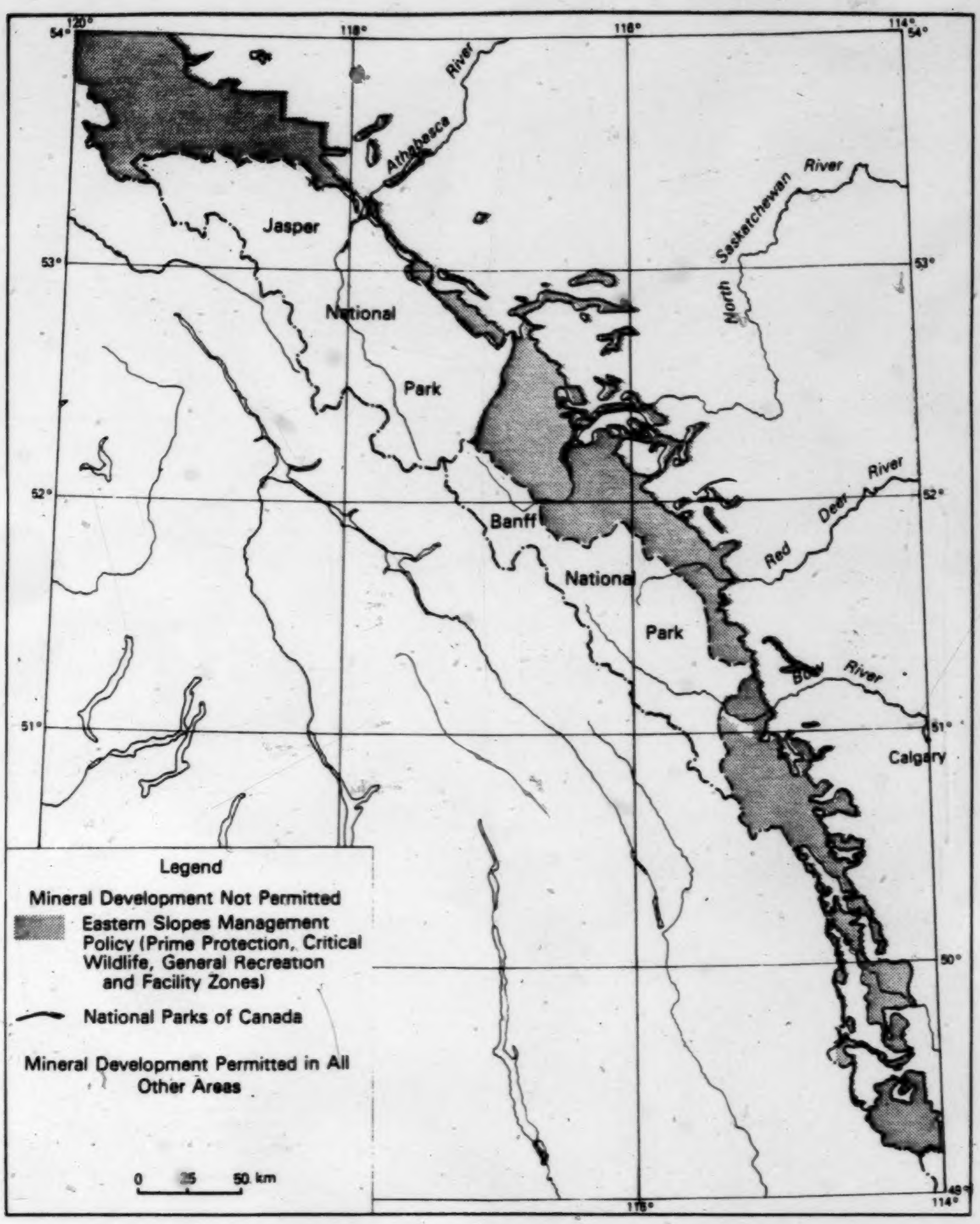
120°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Athabasca River
Jasper
National
Park
North Saskatchewan River
Red Deer River
Banff
National
Park
Bow River
Calgary
Legend
Mineral Development Not Permitted
▨ Eastern Slopes Management Policy (Prime Protection, Critical Wildlife, General Recreation and Facility Zones)
National Parks of Canada
Mineral Development Permitted in All Other Areas
0 25 50 km

Figure 1. Restrictions on mineral exploration and development — Cordilleran of Alberta

Phosphatic - An adjective for a rock type containing an anomalously high amount of phosphate (when compared to the crustal average, about 0.27% P_2O_5). Rocks containing 1.0% or more P_2O_5 are herein defined to be "phosphatic".

P_2O_5 - Standard means of expressing phosphorous content of phosphate rocks or fertilizers as phosphorous pentoxide. Other forms used to express phosphorous content include:

BPL (Bone Phosphate of Lime) = $2.1852 \times P_2O_5$

P (Elemental Phosphorous) = $0.4364 \times P_2O_5$.

Phosphate Rock - Commercial term used to denote a rock type that can be economically mined and used for its phosphorous content in the production of phosphate fertilizers or elemental phosphorous.

B. Industrial and Economic Aspects

Primary Uses of Phosphates

Phosphate rock is used in Canada to produce four main products: elemental phosphorous, phosphoric acid, phosphatic fertilizers and phosphate chemicals.

Elemental phosphorous is produced at two plants in Eastern Canada (Varennes, Quebec and Long Harbour, Newfoundland) and is used to produce technical and food grade phosphoric acid for use in the food industry. Elemental phosphorous is also used to produce red phosphorous sesquisulfide, an important commodity used in steel making and in the match industry. Canadian consumption of Florida-derived phosphate rock for the elemental phosphorous industry amounts to about 600,000 t per year (Energy, Mines and Resources, 1982).

Phosphoric acid is produced at nine plants across Canada (Table 1), most of the product being used in the manufacture of various types of fertilizers, with a minor amount used to produce calcium phosphate.

Phosphatic fertilizers are produced in the same nine plants mentioned previously (Table 1). Fertilizers produced are mainly of the ammonium phosphate variety and include diammonium phosphate (18-46-0), monoammonium phosphate (11-48-0 to 11-55-0) and ammonium phosphate-sulfate (16-20-0-14). Total Western Canadian production of these fertilizers amounts to 622,000 t P_2O_5 per year (Table 1).

Phosphate chemicals, mainly calcium and secondarily sodium phosphates, are produced at two eastern Canadian plants and are used mainly as animal feedstocks, in the paper industry, and in the detergent/soap industry. Some ammonium phosphate is produced for use in the manufacturing of fire retardants.

Methods of Treatment, Industrial Grades and Requirements

Canadian fertilizer plants are designed to accept raw phosphate rock in the 31.1 to 33.0 percent P_2O_5 range. The first step in the production of fertilizers is producing phosphoric acid. This is done by either the "dry" or "wet" process. In the dry process, phosphate rock is thermally reduced to elemental phosphorous in a furnace. The P is then oxidized to form P_2O_5 and finally absorbed in water to yield H_3PO_4. This process produces a very high quality acid, however the high cost involved usually precludes it as the most favorable method in making fertilizers.

The wet process involves acidulating raw phosphate rock, finely ground to 200 mesh sieve size, with a strong acid such as sulfuric, nitric, phosphoric or hydrochloric. Sulfuric acid is the favored one because of its low cost, high availability in Western Canada, and lower corrosiveness. Useable energy is also generated by the exothermic reaction of making sulfuric acid; which in turn acidizes the phosphate rock (Nielson and Janke, 1980). This process is shown by the reaction:

rock phosphate + sulfuric acid $\rightleftharpoons$ phosphoric "filter" acid + gypsum crystals + hydrofluoric acid $(Ca,Na)_5(PO_4,CO_3)_3(F,OH) + H_2SO_4 \rightleftharpoons H_3PO_4 + CaSO_4 \cdot 2H_2O + HF$

The resulting crystalized gypsum is removed and the "Filter Acid" (26 to 30% P_2O_5) is evaporated under vacuum to produce a more concentrated "plant phosphoric acid" (40 to 44% P_2O_5) or higher grade "commerical" or "merchant" grade (45 to 54% P_2O_5) acid. "Superphosphoric" acid, though not widely produced in Canada, is formed by further concentration to the 69 to 72% P_2O_5 range. Plant phosphoric acid is usually then

Table 1. Canada, Phosphate Fertilizer Plants, 1981 (From EMR, 1982).

			BASIS FOR		
COMPANY	PLANT LOCATION	ANNUAL CAPACITY (TONNES P_2O_5)	PRINCIPAL END PRODUCTS	SOURCE OF PHOSPHATE ROCK	H_2SO_4 SUPPLY FOR FERTILIZER PLANTS
Eastern Canada					
Canada Wire and Cable Limited	Belledune, N.B.	150 000	am ph	Florida	SO_2 smelter gas
C-I-L Inc.	Courtright, Ont.	90 000	am ph	Florida	SO_2 smelter gas, pyrrhotite roast and waste acid
International Minerals & Chemical Corporation (Canada) Limited	Port Maitland, Ont.	118 000	H_3PO_4, as ts, ca ph	Florida	Sulphur, and SO_2 smelter gas
		358 000			
Western Canada					
Cominco Ltd.	Kimberley, B.C.	86 000	am ph	Montana and Utah	SO_2 pyrite roast
	Trail, B.C.	77 300	am ph	Utah	SO_2 smelter gas
Esso Chemical Canada	Redwater, Alberta	204 000	am ph	Florida	Sulphur
Sherritt Gordon Mines Limited	Fort Saskatchewan Alberta	50 000	am ph	Florida	Sulphur
Western Co-operative Fertilizers Limited	Calgary, Alberta	140 000	am ph	Idaho	Sulphur
	Medicine Hat, Alberta	65 000		Idaho	
		622 000			
Total, phosphate fertilizer		980 000			

am ph ammonium phosphates; ss single superphosphate; ts triple superphorphate; ca ph food supplement calcium phosphate; H_3PO_4 phosphoric acid for commercial sales.

transferred to the fertilizer production units where varying amounts of ammonia are added. The final step is the formation of uniform size granules, and the drying of the granules.

The overall production of ammonium phosphate fertilizers by the wet process is about 88-92% efficient in recovering the available P_2O_5 in the raw phosphate rock.

The Canadian phosphate fertilizer industry imported a total of 3.6 million t of phosphate rock in 1981 (Energy, Mines and Resources, Canada, 1982) at an estimated cost approaching $250 million dollars (U.S.).[2]

Western Canadian Fertilizer Industry

Five fertilizer companies operate seven plants across western Canada (Table 1), for a total fertilizer capacity of approximately 1.386 million t (Nielson and Janke, 1980), utilizing 2.095 million t (Energy, Mines and Resources, 1982) of phosphate rock in the process. Cominco, Simplot and Western Co-operative Fertilizers all own and operate their own phosphate mines in Utah, Idaho and Montana. The other producers obtain phosphate from Florida via shipping up the west coast to Vancouver and then rail transport to Alberta. A small quantity (usually less than 1,000,000 t) has been imported annually from the Netherlands, Antilles, Morocco, Israel and Niger in the past thirty-six years. This quantity of non-American phosphate rock has dropped to less than 100 t in the 1980's.

Future Canadian Supplies of Phosphate Rock

Canada has been dependent on U.S. exports of phosphate rock since about 1912 when the fledgling Canadian phosphate mining industry died. No disruption of this supply is anticipated through the 1980's. By the year 1991, however, reserves of the better Florida rock will be exhausted, and leaner grade ores will be mined, so that exports of raw phosphate rock will be replaced by a more upgraded product (Weaver and Thomas, 1978). By the next century it is anticipated that U.S. domestic demands will equal production capacity - and thus U.S. available rock for exports will gradually drop off (U.S. Bureau of Mines, 1981).

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[2] Based on $64/t (U.S.)

At this time (2000 A.D.) Canada may have to look for alternate supplies of phosphate rock. These alternatives include Mexico (which at the present time is trying to estabish a phosphate mining industry based on the Baja California deposits), Morocco, or Africa in general (which is estimated to hold 68% of the world reserves of phosphate). Another alternative would be a examination of Canadian phosphate deposits. Promising Canadian deposits include the carbonatite hosted apatite deposits of eastern Canada (e.g. Cargill or Nemegos deposits) and the sedimentary phosphorites of Western Canada that are dealt with, in part, in this report.

Uranium, Vanadium and Fluorine Resources in Phosphates

Phosphates contain significant amounts of a number of potentially exploitable elements, which could be extracted as byproducts. Uranium, vanadium, fluorine and a number of rare earth elements are most commonly reported, and the abundance of these elements was evaluated in this study.

Uranium has probably the best potential for recovery as a byproduct in a phosphate processing plant. Uranium is easily extractable in phosphate rock acidizing procedures (DeVoto and Stevens, 1980) and one fertilizer plant in southern Alberta is doing this, from imported phosphate rock (Energy Mines and Resources, 1982). DeVoto and Stevens (1980) estimated that if U.S. phosphates were mined solely for their uranium content the cost would be in the $175 - $250 (U.S.)/lb (1979 dollars) range and these uranium phosphate reserves could supply all the Free World demands until about 2025. Uranium pricing reached a peak in about 1976 ($U.S. 40/lb U_3O_8), stabilized and started a downturn in 1979 continuing to the present 1984 price of ($U.S. 17.50/lb U_3O_8). The present downturn is seen as a minor event, in an overall increasing market demand situation (Whillans, 1980). Market demands are expected to pick up by the late 1980's to early 1990's and continue to be high through to 2025. World production is expected to keep pace with demand until about 1995, at which time, production capability from known sources (including phosphates) will begin to fall and be overtaken by world demand (Whillans, 1980). For the short term, the next decade, the outlook for uranium potential from phosphates is not encouraging, but it looks more promising into the 1990's.[3]

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[3] This is about the time that the U.S. export market in phosphate rock, particularily to Canada, may start to decrease as domestic U.S. consumption

Vanadium's principle use is in the iron and steel industry as ferrovanadium or vanadium-carbon ferroalloys. The price of vanadium has shown a slow steady increase from about $2.70 (U.S.)/lb ($V_2O_5$) in 1973 to about $6.25 (U.S.)/lb in 1982 (Kuck, 1983). Very little vanadium is produced in Canada, however the Canadian steel industry imported nearly 0.5 million pounds of vanadium compounds from the U.S. in 1980 (Kuck, 1980). One phosphate mine in Idaho is currently (1982) producing vanadium as a byproduct (Kuck, 1983).[4] World production of vanadium exceeds demand, and at the present time the vanadium market is somewhat slumped. The future market potential is expected to increase, worldwide by about 2.9%/year until the year 2000 (Kuck, 1983).

Fluorine, as "Fluorspar" (CaF_2), is used in the chemical, ceramics, and steel industries refining uranium ores. The chemical (producing HF acid) and steel industries account for 97% of the U.S. production. Canadian production of fluorspar ceased in 1977, and most fluorspar is now imported from Mexico.

Fluorine is recovered as flurosilic acid from two phosphate rock processing plants in Canada (Erco Industries, Ontario; Cominco Ltd., British Columbia) (Boyd, 1980) and eleven plants in the U.S. However, most fluorine available from phosphate processing plants is not recovered and is usually dumped in settling ponds. Phosphate rock in the U.S. commonly contains 3.5% fluorine, and given the 1973 estimates of phosphate rock reserves in the U.S. (10.5 billion tons), there are approximately 740 million tons of fluorspar present (Grogan and Montgomery, 1975). This is an enormous quantity given that the total world production of fluorspar (1980) was a little over 5 million tons (Morse, 1980). The price of fluorspar in 1980 was between $93 - 122 (U.S.)/short ton. Flourspar production is governed to a large extent by the steel, chemical and aluminum industries. Very little growth in the industry was experienced throughout the 1970's, and only modest growth is predicted in the steel-aluminum usage areas. The chemical industry is seen as the best user of fluorine in the longer term (Boyd, 1980).

A number of rare earth elements (REE) are found in phosphates in anomalously high quantities. Some REE were produced in Canada as byproducts from uranium and base metal mines up until 1973, but production has since ceased. Yttriuum was the main element produced, with many of the other REE being present. Australia, and the United

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[3](cont'd) exceeds production.

[4] J.R. Simplot Company, Gay, Bingham Company mine

States are the major REE producers, with a total world production (1978) of nearly 40 thousand short tons (Cranstone, 1980). The REE vary in price, depending on element, from $7(U.S.)/lb for Lanthanum to $900 (U.S.)/lb for Europium (Cranstone, 1980). Little is known about the future supply/demand situation with respect to the REE.

C. Phosphates - General Information

Mineralogy

By far the most common mineral of the sedimentary phosphates is the carbonate fluorapatite mineral, francolite $(Ca_5PO_4)_3(F,CO_3)$. Francolite differs from fluorapatite $(Ca_{10}(PO_4)_6F_2)$ in that 3-6% of the mineral weight of PO_4^{-3} is commonly replaced by CO_3^{-2}. The resulting charge difference is partly compensated for by various substitutions such as Ca^{+2} Na^{+1}, PO_4^{-3} SiO_4^{-4} or PO_4^{-3} CO_3F^{-3} (Bentor, 1980). Fluorine is usually present in quantities exceeding 1%. Francolite commonly crystallizes as cryptocrystalline, equidimensional spherulites, and appears pseudo-isotropic under crossed nicols. A direct relationship exists between increasing CO_3^{-2} substitution in fluorapatites with decreasing crystal size, and hence lower birefringence. Recrystallized, fibrous francolite is typically a low-birefringent brown color under crossed nicols (Plate 7A and 7B).

Pure fluorapatite is rare in sedimentary phosphates, being confined mainly to igneous rocks, although it is thought to occur in some of the Alberta phosphate deposits. Low CO_2 values, and a first order gray birefringence characterize fluorapatite.

Carbonate-hydroxyapatite, in the form of dahllite $(Ca,X)_{10}(P,C)_6(O,OH)_{26}$ where $X=Na^+, Sr^{+2}, K^+, Mg^{+2}, Ba^{+2}, Al^{+3}, Fe^{+2}, Mn^{+2}$ or U^{+4} is characterized by CO_2 values (a reflection of CO_3^{-2} content) greater than 1%, fluorine less than 1%, and a white or gray-white birefringence. Dahllite is often a secondary phosphate mineral that forms crusts or represents original bone material (Plate 8C).

While many more varieties of phosphate minerals exist (see Wenchel and Wenchel, 1956 or McConnell, 1973), francolite, fluorapatite and hydroxyapatite are the only ones identified in this study.

Textural Forms

Although the mineralogy of phosphates identified in this study is fairly straightforward, the textural forms that the apatite minerals take are varied. Most authors describing individual phosphate deposits devise their own classification schemes to elucidate the various textural expressions of the phosphate minerals (Riggs, 1979, Birch, 1980). This author, in keeping with tradition, will offer his own scheme to describe petrographic textural types of sedimentary phosphates found within the Alberta-British Columbia Cordilleran region, in strata of Devonian to Middle Jurassic age. Table 2 summarizes this scheme. Five basic textural types are recognized: pellets, cements, intraclastic material, nodules, and fossil material. Examples of each of the five types and the various subdivisions are given in Table 2.

Phosphate Deposition

The deposition of sedimentary phosphate deposits is, at the present time, thought to be dependent upon seven basic processes (Sheldon, 1981). As phosphate deposition basically involves the chemical precipitation of apatite, it is likely that the geochemical processes are the most fundamental ones. The other processes either bring about favorable geochemical conditions or serve to upgrade deposits that are forming. These seven basic processes are by and large time-sequential and interdependent, one process leading to the next. If the conditions necessary for anyone of the seven processes are not met, no significant accumulation of phosphate will occur. These seven processes are as follows[5]:

1. A supply of phosphorous.
2. Storage and accumulation of oceanic phosphorous.
3. Upwelling of stored phosphorous to shallower levels.
4. Concentration of phosphorous at the ocean floor from organic material, derived from biota that flourished in upwelling zones.
5. Correct chemical conditions to induce apatite precipitation.
6. Apatite precipitation by biogenic, diagenetic and/or primary sea floor precipitation.
7. Concentration of phosphate deposits to economical deposits.

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[5] The following section is based largely upon the work of Sheldon, 1981, and Cook, 1976.

Table 2. Classification of Alberta Phosphate Petrographic Textural Forms.

TYPE	DESCRIPTION	EXAMPLES			
		AGE	SECTION NO.	HORIZON **	PLATE
1. Pellets	- rounded to subrounded oval shaped				
a) Oolitic (P1)	- concentric layers visible	Permian	290	RCBP	6F
b) Nucleated (P2)	- pellet formed around detrital core	Triassic	45	LWMP	8D
c) Structureless (P3)	- no internal structure visible	L. Jurassic	205	BFP	9A
d) Elongated (P4)	- elongate pellets in an argillaceous matrix	L. Jurassic	375	BFP	10C
2. Cements					
a) Conglomerates/ Breccias (C1)	-cement supporting a chert, dolostone, clast conglomerate/breccia	Permian	146	RCBP	6E
b) Sandstones (C2)	- supporting a "floating" sandstone	Permian	290	RCBP	6F
c) Siltstones (C3)	- supporting a "floating" siltstone	Permian	295	JCIP	6C
d) Microsphorite (C4)	- well laminated, primary (?) cement	Devonian	228	MPH	5C
e) Fluorapatite (C5)	- pure fluorapatite	Helikian	*	*	4F
f) Francolite (C6)	- pure carbonate fluorapatite	Permian	116	MBP	7A
3. Intraclasts	- transported material				
a) Small-clastic debris rich (I1)	- filled with clastic material	L. Fernie	103	BFP	10B
b) Pebbles (I2)	- reworked microsphorite (?), no clastic debris	Permian	64	RCBP	7D
4. Nodules					
a) Diagenetic (N1)	- clastic material within nodule same size as that outside the nodule	Mid Jurassic	13	RCUP	10D
5. Fossils					
a) Bones, teeth (F1)	- phosphatized bones and teeth	Triassic	45	LWMP	8C
b) Shells (F2)	- shell remains, phosphatic	Triassic	386	LWMP	8A

* Photograph donated by J. Wilson, Alberta Geological Survey. From the Wolverine Point Formation in northeastern Alberta.

** RCBP - ranger canyon basal phosphate, LWMP - lower whistler member phosphate, BFP - basal fernie phosphate, JCIP - johnston canyon intraformational phosphate, MPH - middle phosphate horizon (Exshaw Fm.), MBP - mowitch basal phosphate, RCUP - ranger canyon upper phosphate

Phosphorous Supply to Oceans and Lakes

The phosphorous cycle begins with the chemical erosion of rocks and soil containing phosphorous minerals, taking the phosphorous into solution (as organic and inorganic compounds), transporting the phosphorous via rivers and groundwater, and finally deposition in the oceans or lakes. The bulk of the volume of phosphorous added to oceans is, however, as detrital mineral grains, not as phosphorous in solution. An amount equivalent to about half that contibuted by dissolved phosphorous is added by volcanic and crustal spreading centers. At the present time the estimated total amount of phosphorous entering the oceans from all sources is 1.57 x 10^6 t per year.

Storage of Phosphorous

Surface oceanic waters normally tend to become depleted in phosphorous by living organisms incorporating phosphorous and downward transportation at death. From about 200 metres down to 1000 metres phosphorous concentrations remain approximately constant, though increasing slightly with depth to a maximum at about 1000 metres. Apatite is more soluble in colder, deeper water, a function of decreasing temperature and increasing pressure, and so the deeper ocean basins tend to become sinks, enriched in dissolved phosphorous. Deep ocean vertical circulation is a slow process, and is only speeded up by changing sea levels (major transgressions or regressions), tectonic displacement of continental blocks, oceanic currents, and changing wind patterns. Cook and McElhinny (1979) noted a cyclic pattern to phosphate deposition throughout Phanerozoic time, with the Cambrian, Permian, Jurassic / Cretaceous boundary, Paleocene, Eocene, Miocene and Pleistocene containing large and numerous deposits. Sheldon (1980) suggested that this cyclicity was related to the development of deep ocean phosphorous sinks, and their eventual turnover during later time periods. This turnover brings about upwelling and precipitation of apatite, as will be discussed in the next sections. Thus some geological periods were favorable for the accumulation and storage of phosphorous and others were more favorable for the deposition of phosphorous as apatite.

Deep Oceanic Turnover to Shallow Water

In order to tap the vast amounts of phosphorous available in the deep oceanic basins, some mechanism must be evoked to circulate the well stratified oceanic waters. This mechanism is "upwelling" and is known to take place in a number of different settings:

1. Ocean currents flowing parallel to coastlines and reinforced by prevailing winds.
2. Oceanic currents flowing up to and over a high submarine topographic feature, termed "dynamic upwelling".
3. In the Trade Wind belt, at low latitudes (0-25°).
4. Along the north and west coasts on continents in the northern hemisphere, at low latitudes (0-25°).
5. Along coasts of land masses having very dry climates.
6. In coastal areas in the Westerly Wind belt between 20 - 40° latitude.
7. Large ocean basins with open accesses to polar regions.
8. Along the equator.
9. Antarctic upwelling.

Upwelling is seen as the essential process whereby a steady supply of phosphorous-bearing waters can be delivered to shallower (relatively) accumulation sites. Upwelling has been invoked to adequately explain many types of deposits (e.g. Phosphoria Fm, Florida, Morocco deposits), however it becomes more difficult to use when the depositional environments are clearly very shallow water (e.g. estuarine, fluviatile or tidal flat settings, Cook, 1976).

Concentration of Phosphorous at the Ocean Bottom

The net result of upwelling is a proliferation in the upwelling area of plankton, diatoms, and other biota, all utilizing the phosphorous in their life processes. Upon death, these organisms settle to the sea floor, where some of the phosphorous returns to the ocean water and some is concentrated in the interstitial sediments. Sulfate and iron reduction is known to be instrumental in the breakdown of organic material and the releasing of phosphorous. Much of this interstitial phosphorous is returned to the water column during early diagenesis, however some remains in the sediment and becomes highly concentrated.

Apatite Solubility and Chemistry

Apatite precipitation is controlled by the following reaction:

$$Ca_5(PO_4)_3F \rightleftharpoons 5\ Ca^{+2} + 3PO_4^{-3} + F^{-1},$$

$$SP = [Ca^{+2}]^5[PO_4^{\ -3}]^3[F^{-1}]$$

When the concentration of PO_4^{-3} ion is increased to the point where the solubility product "SP" is exceeded, apatite precipitates or the reaction proceeds to the left. The PO_4^{-3} concentration is pH-dependent. The pH, in turn, is primarily controlled by dissolved CO_2, forming carbonic acid, the pH being lowered as CO_2 content increases. PO_4^{-3} also forms a number of complex ions, the ion $MgHPO_4$ being probably one of the most important in reducing the overall concentration of PO_4^{-3} and thereby inhibiting the precipitation of apatite.

The SP of this reaction is also affected by temperature and pressure, increasing with decreasing temperature and increasing pressure. The same temperature/pressure effect also increases the partial pressure of CO_2, thereby decreasing the pH of the water. Undersaturation of the ocean water with respect to apatite is the end result of both temperature/pressure effects.

Current oceanographic studies combined with paleo-oceanographic work suggest that the ocean is and was probably close to saturation or slightly under saturated with respect to apatite. However, very few, if any, modern day examples exist of apatite precipitating directly out of the water column, onto the sea floor. It has been found that interstitial sediment pore waters are highly concentrated with respect to apatite, in some cases several hundred times that of normal seawater, due to the decomposition of organic matter. It is therefore in that zone, immediately below the sediment/oceanic water contact, that researchers see many phosphorites having formed in the past. Here, PO_4^{-3} concentrations could readily cause the SP to be exceeded and apatite to be precipitated.

Apatite Precipitation

Apatite is precipitated in three basic ways: as a primary biogenic material, by diagenetic precipitation in ocean floor sediments, and by primary precipitation at the sediment-water interface.

Primary Biogenic

Biogenic material within this group includes: shells of some brachiopods, bones and teeth of vertebrates, fish scales, conodonts, and mollusc kidney stones. All of this material, of which apatite is a major component, is precipitated within life forms and can form discrete phosphate-rich beds upon accumulation.

Primary Precipitation on the Sea Floor

Although no modern deposits of this type have been found, and modern sea water chemistry suggests that they may not exist - there still remains a large body of evidence from ancient deposits that says this type of precipitation did go on in the past (Cressman and Swanson, 1964; Sheldon, 1963; Cook, 1976). Two types of phosphate in particular are said to be indicative of primary precipitation: quartz-cored apatitic oolites and finely laminated, bedded phosphorites, or mudstones (Sheldon, 1981). Disagreement still exists however, with other workers (Cook, 1976) suggesting a diagenetic replacement of carbonate precursors for both quartz-cored oolites and bedded phosphorites.

Diagenetic Precipitation

In the early years of phosphate research all phosphates were thought to be precipitated directly out of sea water and onto the ocean floor (Kazakov, 1937). Subsequent oceanographic work failed to locate any modern day examples of deposits formed in this way. Further it was discovered that sea water may be only close to saturation with respect to apatite, but was certainly not oversaturated. Interstitial pore waters in modern sediments were found to be supersaturated with respect to apatite. Phosphate pellets, and nodules were subsequently found within modern muds (Burnett, 1977) as well as apatite replacing limestones and calcareous shell fragments. Thus a rich source of PO_4^{-3} was discovered (i.e. interstitial pore waters), driven by the degradation of organic matter which in itself was produced by oceanic upwelling. Many ancient deposits were and still are attributed to diagenetic phosphate precipitation.

Concentrations of Apatite

The concentration of precipitated phosphates to form high grade economically attractive deposits is the final step in phosphogenesis. Winnowing, reworking and weathering are thought to be the three most important processes.

Depositional Models

Ten primary factors are thought to be the most important in developing any model explaining phosphate sedimentation (Burnett and Sheldon, 1979):

1. Paleogeographical, and paleoclimatic setting
2. Paleooceanography: currents, chemical characteristics, etc.
3. Plate tectonic setting
4. Local tectonic setting
5. Type of phosphate deposited
6. Associated sediments-vertical and lateral facies changes
7. Sedimentation rate
8. Diagenesis
9. Sediment transport and reworking
10. Weathering.

Several different "types" or "classes" of models can be applied to phosphate sedimentation, such as: analogue models, depositional environment models, tectonic setting models, primary mode of formation models, principal phosphate textural type models, or conceptual genetic models (Burnett and Sheldon, 1979).

Conceptual genetic models are perhaps the most all-encompassing and usually attempt to reconcile the other model types and the ten primary factors listed above into a unified reasonable single model. Nine basic genetic models of phosphate deposition are in vogue today and are summarized in Table 3. Details of these models can be found in Cook, 1976; Sheldon, 1981; and Christie, 1979.

Table 3. Summary of Phosphate Depositional Models.

MODEL TYPE	OCEANIC CURRENTS	DEPOSITIONAL AREA	LITHOLOGIC ASSOCIATIONS	INFERRED WATER DEPTH	TEXTURAL PHOSPHATE TYPES	PLATE TECTONIC SETTING	ASSOCIATED FAUNA	EXAMPLES
West coast Shelf Margin	upwelling along west coasts	shelf margin	chert, black shale	hundreds of metres	pellets, minor oolites	Geosynclinal sub- or obducting plate boundaries	Pelagic	Phosphoria Fm, USA Sechura deposits, Peru Fernie Fm., W.Canada
East-West Shelf Margin	upwelling along south side of east-west coasts	shelf margin?	chert, black shale	?	?	?	Pelagic?	Iran, Morocco, Columbia, Cambrian deposits of China
East-caost shelf margin	Dynamic Upwelling?	shelf margin	Mg-rich clays Glauconites Dolomite	?	?	?	Pelagic?	Varswater, S. Africa Hawthorn Fm., USA
Epicontinental Platform	Dynamic Upwelling	Flanks of anticlines and within synclines	Carbonates sandstones	shallow water (tens of metres)	pellets, nodules, microphorite	not important	shallow water	London and Paris Basins
Insular	Not important	Islands - Equatorial regions	Corraline limestones	Subaerial Exposure	guano	not important	terrestrial	Naru Ocean Islands
Unconformity	?	Shallow shelf	Conglomerates sandstones	very shallow	cements minor pellets	not important	very shallow water	Permian, Alberta
Fossil and Shell Beds								Parts of Phosphoria, Fm., Upper Exshaw, Alberta
Tidal Flat Estuarine		Tidal Muds of Estuaries	shale, dolomite, sandstone, siltsones	very shallow	microsphorite oolites		very shallow water	Part of Sulphur Mountain Fm, Alberta, S.W. Africa
Reworked	Fluvial or Marine Currents	Fluvial systems	conglomerates sandstones	very shallow	pebbles Intraclasts			Florida Parts of Permian, Alberta

D. General Geology

Phosphate Occurrence in Alberta

General Historical Geology

Phosphate is found in ten geological formations which outcrop in the Cordilleran region of Alberta and southeastern British Columbia (Figs. 2 and 3). [6]All of the strata now exposed in the Cordilleran were deposited in the Alberta trough or on the adjacent eastern platform (Fig. 2). From the Cambrian to about Middle Jurassic, sediment was derived from a landmass to the east, now on the Canadian Shield. From Upper Jurassic to Tertiary, a molasse sequence of sediments was shed from a rising orogenic belt, where once the Alberta trough had been situated (McCrossan and Glaister, 1964). The major tectonic elements that influenced sedimentation during the main phosphatic depositional periods from Late Devonian to Middle Jurassic are shown in Figure 2.

Phosphate was deposited in the Late Devonian-Mississippian Exshaw Formation, the Pennsylvanian Spray Lakes Group, the Permian Ishbel Group, the Triassic Spray River Group, and the Jurassic Fernie Group. The Exshaw, Ishbel and Fernie phosphates are the most widespread and are the ones of main economic interest.

The Upper Devonian in Alberta saw the development of reefs and extensive carbonate shelf platforms, one of which is the Palliser Formation, upon which the Exshaw sits. The deposition of the Exshaw and equivalent units represented a continent-wide transgressive period, with black shales being the dominant sediment. Phosphates are found within the lower part of the Exshaw Formation and may represent brief interruptions in sedimentation.

Mississippian sedimentation in Alberta was continuous and dominated by thick transgressive shale/limestone sequences in the Lower Mississippian, and a return to carbonate shelf environment on the Alberta Shelf in Upper Mississippian times.

The Pennsylvanian-Permian time is represented by coarse clastic sequences and numerous breaks in the stratigraphic record suggest several erosional episodes. It is suspected that sedimentation took place primarily in the Alberta Trough and that much of

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[6] Six occurrences are found in formations outside of this region, in the Western Canada Sedimentary basin (Fig. 2).

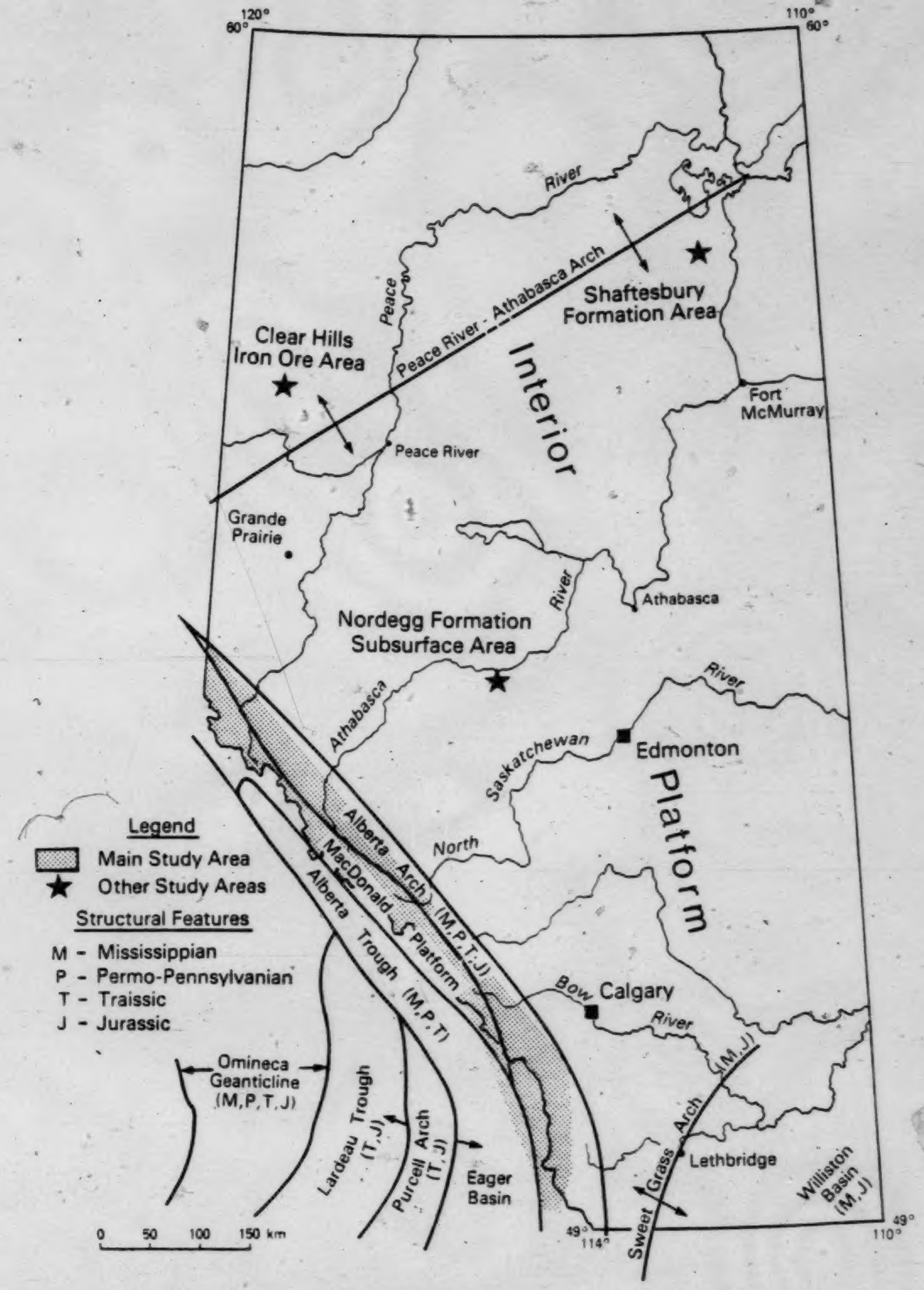
120°
60°
110°
60°
River
Peace
Peace River - Athabasca Arch
Shaftesbury
Formation Area
Clear Hills
Iron Ore Area
Interior
Fort
McMurray
Peace River
Grande
Prairie
Athabasca
River
Nordegg Formation
Subsurface Area
Athabasca
River
Saskatchewan
Edmonton
Platform
North
Alberta Arch (M,P,T,J)
MacDonald Platform
Alberta Trough (M,P,T)
Bow
Calgary
River
(M,J)
Sweet Grass Arch
Lethbridge
Williston
Basin
(M,J)
Legend
Main Study Area
Other Study Areas
Structural Features
M - Mississippian
P - Permo-Pennsylvanian
T - Traissic
J - Jurassic
Omineca
Geanticline
(M,P,T,J)
Lardeau Trough
(T,J)
Purcell Arch
(T,J)
Eager
Basin
0
50
100
150 km
49°
114°
49°
110°

Figure 2. Study areas and major tectonic elements — Alberta phosphate study

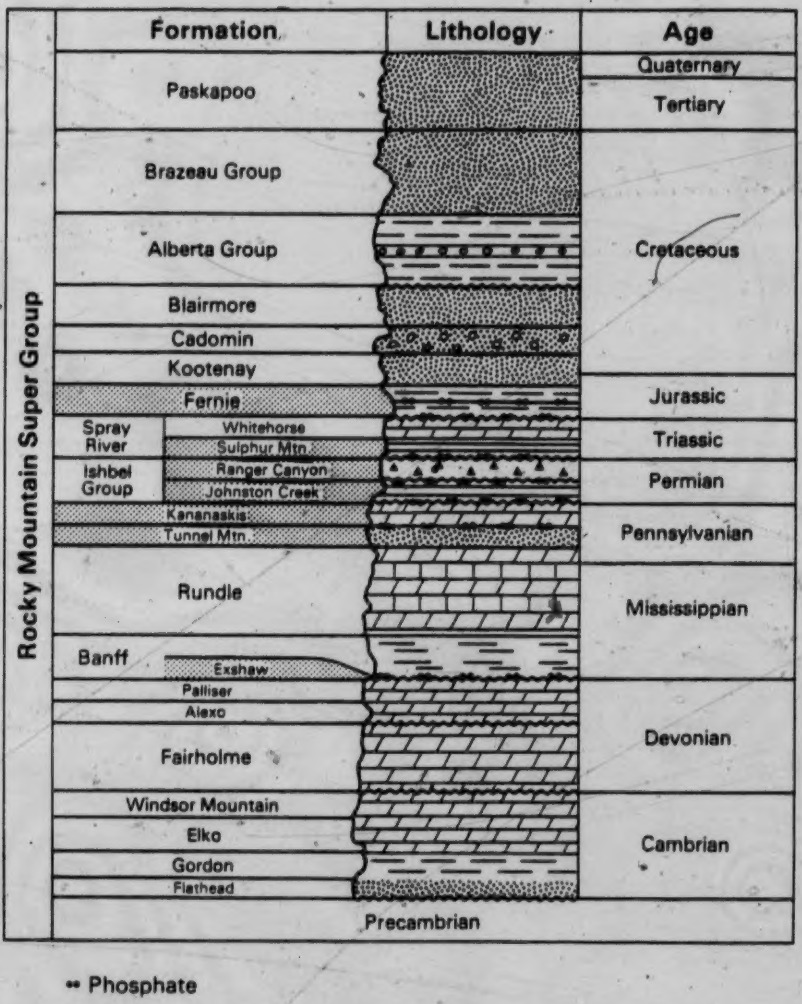
Formation
Lithology
Age
Rocky Mountain Super Group
Paskapoo
Brazeau Group
Alberta Group
Blairmore
Cadomin
Kootenay
Fernie
Spray River
Whitehorse
Sulphur Mtn.
Ishbel Group
Ranger Canyon
Johnston Creek
Kananaskis
Tunnel Mtn.
Rundle
Banff
Exshaw
Palliser
Alexo
Fairholme
Windsor Mountain
Elko
Gordon
Flathead
Precambrian
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Pennsylvanian
Mississippian
Devonian
Cambrian
•• Phosphate

Figure 3. Generalized stratigraphic section — Cordilleran region and major phosphate bearing units (modified from Jackson, 1975).

the Alberta Shelf was sub-aerially exposed. [7] Phosphate within the Permo-Pennsylvanian is found in various formations, but more commonly at unconformities between formations associated with multiple erosional events (Fig. 3).

The Triassic period is thought to be a series of deltaic / evaporitic deposits, derived from an eastern low-lying landmass (Gibson, 1974). Deposition was confined primarily to the Alberta Trough.[8] Phosphates are found within and at the contacts in members of the Triassic Sulphur Mountain Formation. Uplift and erosion marked the end of the Triassic.

The Jurassic period saw the return of transgressive seas and the deposition of black shales. Phosphates were deposited at the basal contact and within the middle Jurassic sequence (Fig. 19).

Structural Setting

The ten main phosphate-bearing formations are exposed only within the Front Ranges and Foothills of the Cordilleran region. Outcrop configurations are typically narrow and lenticular, broken up and contorted along strike by folding and faulting (e.g. Fig. 8). The distribution pattern is the result of the Laramide orogenic event that produced a series of low angle, imbricate, southwest to westward-dipping thrust faults - thereby breaking up geological formation outcrop patterns (Fig. 4). Fault propogation is generally believed to have progressed from west to east throughout the Laramide orogenic event. Displacements on faults are also generally thought to decrease from west to east. Thrust sheets within the Front Ranges typically extend along strike for several hundred kilometers, terminating in a series of folds and / or simply dying out in the subsurface. Displacement is usually transferred to another thrust sheet, which again carries on for several hundred kilometers. Figure 4 shows the main thrust sheets in the study area, and Figure 5 and Plate 1A shows the typical structural / stratigraphic setting of the main phosphate-bearing formations. It can be seen from Figure 5 that the Exshaw Formation typically is exposed along the eastern flanks of the mountain ranges at high elevations, and is overlain by a considerable thickness of younger strata. The Spray Lakes (Pennsylvanian),

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[7] This is far from certain, as Permo-Pennsylvanian strata are preserved mainly in the Cordilleran and Peace River area, many periods of erosion may have removed Permo-Pennsylvanian rocks. Most units within the Permo-Pennsylvanian do, however, thin rapidly to the east.

[8] Interpretation again subject to post-Triassic erosion that may well have removed Triassic strata from the Alberta Platform

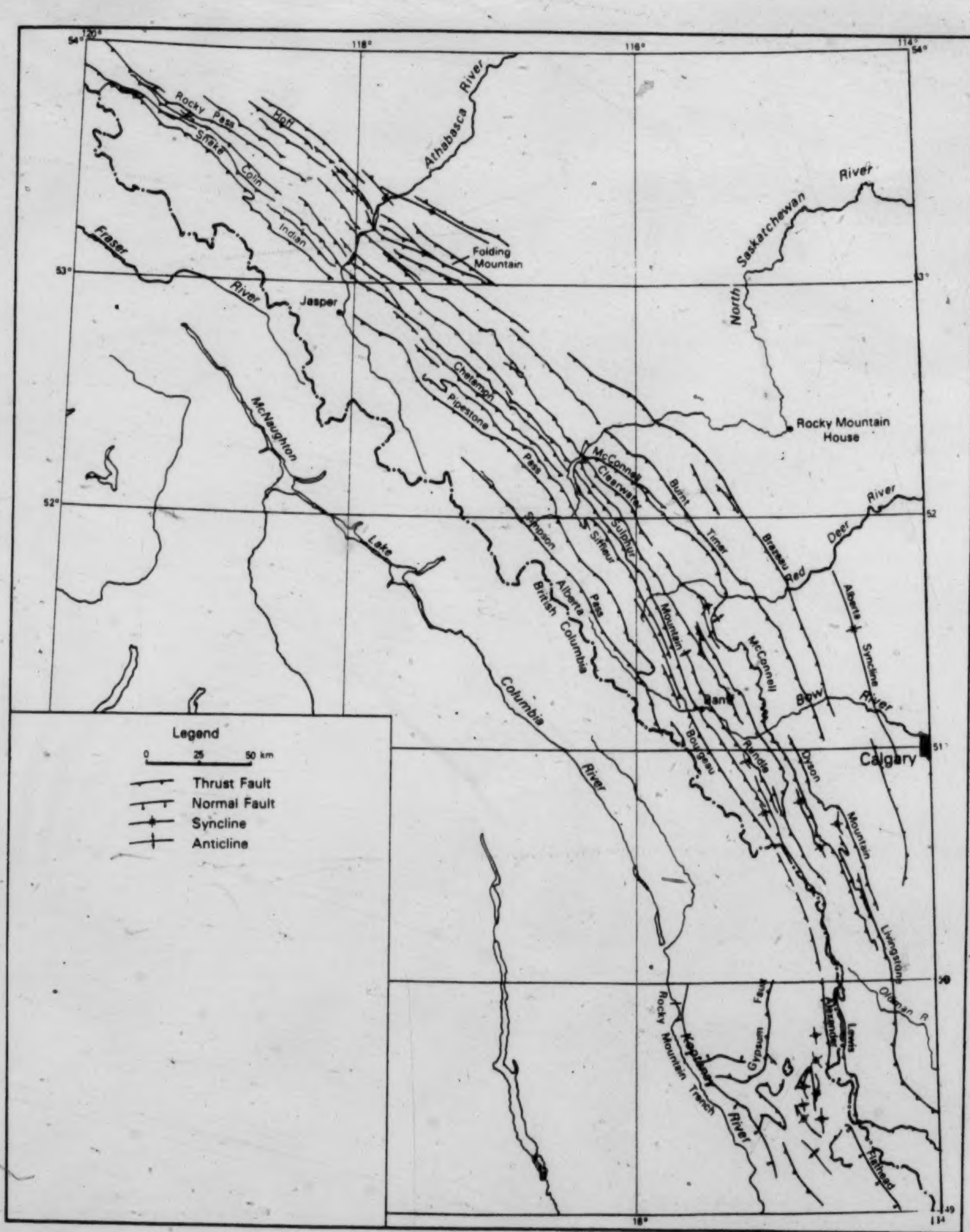
54°
120°
118°
116°
114°
54°
Rocky Pass
Snake
Hoff
Colin
Athabasca River
Indian
Folding Mountain
Fraser
River
53°
Jasper
North Saskatchewan
River
McNaughton
Chatsmon
Pipestone
Pass
Rocky Mountain House
McConnell
Clearwater
Burnt
52°
Lake
Simpson
Siffleur
Sulphur
Timer
Brazeau
Red
Deer
River
Alberta
British
Columbia
Pass
Mountain
McConnell
Alberta
Syncline
Banff
Bow
River
Columbia
Columbia
River
Bourgeau
Rundle
Ozon
Calgary
51°
Mountain
Livingstone
Oldman R
50
Rocky
Mountain
Trench
Kootenay
River
Gypsum
Fault
Alexander
Lewis
Flathead
49
118°
114
Legend
0
25
50 km
Thrust Fault
Normal Fault
Syncline
Anticline

Figure 4. Principal structural elements — Central and southern Canadian Cordilleran, front ranges and foothills

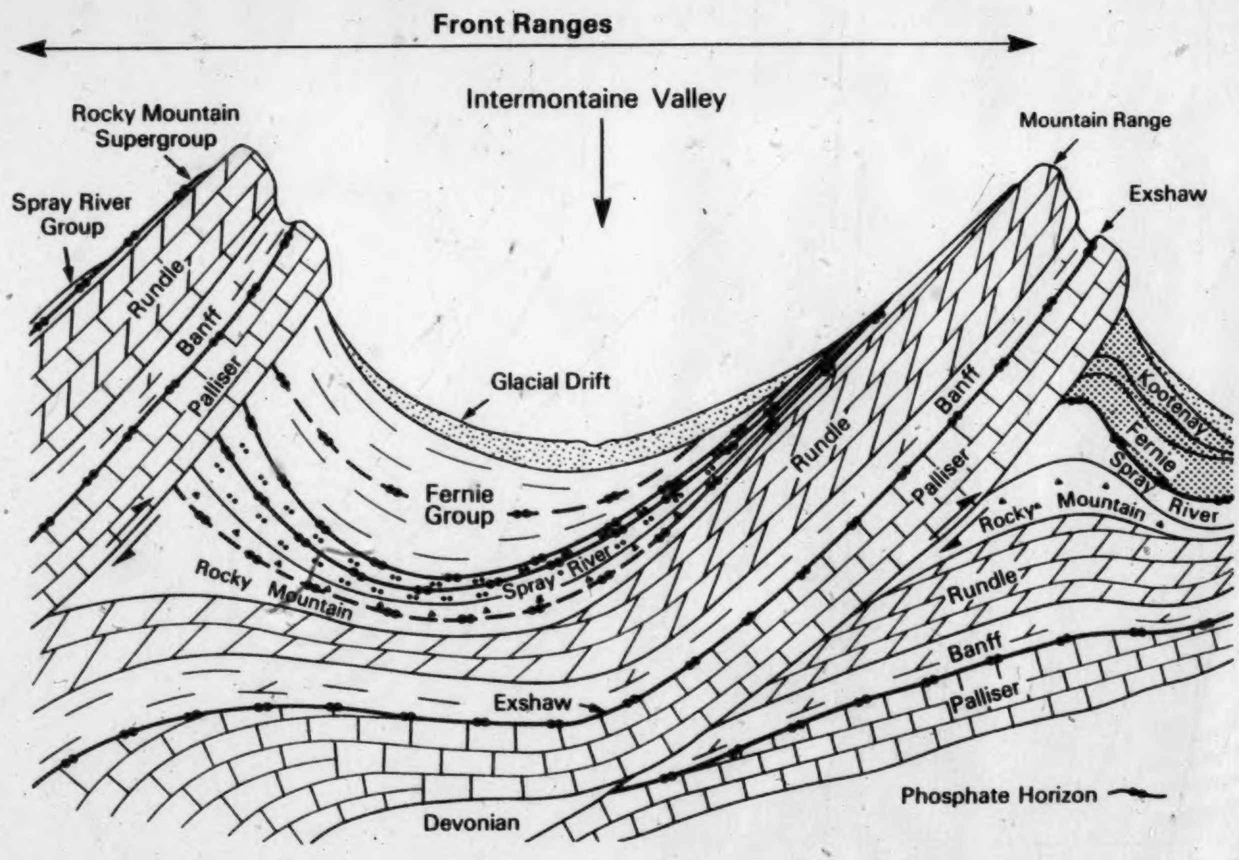
Front Ranges
Intermontaine Valley
Rocky Mountain Supergroup
Spray River Group
Mountain Range
Exshaw
Rundle
Banff
Palliser
Glacial Drift
Fernie Group
Kootenay
Fernie
Spray
River
Rocky
Mountain
Spray
River
Rundle
Banff
Palliser
Rocky
Mountain
Rundle
Banff
Palliser
Exshaw
Devonian
Phosphate Horizon

Figure 5. Idealized sketch of the Canadian front ranges and the typical structural/stratigraphic setting of the main phosphate bearing units

Ishbel (Permian) and Spray River (Triassic) Groups tend to occupy the western "backside" of the ranges, often forming an exposed dipslope. The Sulphur Mountain Formation is a very distinctive unit due to its characteristic reddish-brown weathering color, and is a useful mapping unit throughout the Front Ranges (Plate 1C). The Fernie Group (Jurassic) tends to occupy the valley regions between major thrust sheets (Plate 1A).[9]

All stratigraphic sections presented in this study were palinspastically restored. The resultant paleo-positions are only first approximations based on crude estimates of the displacement along most of the major faults. Displacement estimates were derived using estimates from Norris (1965) and measurements taken from palinspastically restored sections by Price (1981) and Price and Mountjoy (1970).[10] Stratigraphic sections were moved back perpendicular to the average trace of the thrust fault by the estimated displacement distance and the palinspastic position noted. Appendix 1 lists all stratigraphic sections studied, their present and inferred palinspastic position.

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[9] The above remarks are of course only broad generalizations to which many exceptions occur.

[10] Appendix 2 provides a complete list of thrust faults and the displacement applied to them.

II. RESOURCE POTENTIALS

A. Phosphate Resources in Alberta

The general procedure that is used to present the resource potential aspect of phosphates is: 1) a series of maps outlining grade / thickness distribution within a given stratigraphic horizon, and 2) a series of grade / thickness tables. A continuous sequence of strata is taken and weighted average grades are presented that represent both "ore" and "barren" zones[11]. Cross sections are also used to show the stratigraphic position of phosphate-bearing horizons. In cases, where some quantitative data are known these are presented in tables.

A grade / thickness classification scheme for phosphatic rocks has been devised specifically for use within this study and is presented in Figure 6. The scheme provides a common ground for comparing relative resource potential of phosphate showings, by "normalizing" the widely diverse grade / thickness combinations to an assumed minimum mining thickness. Thus, Figure 6 can be used for two purposes: 1) to show the dilution effect on grade when the phosphate zone thickness is adjusted to a minimum mining thickness, and 2) to allow quick comparison of grade / thickness values on a regional basis in order to locate those areas of highest potential.

In the first case, for example, an outcrop of phosphatic strata that averages 22% P_2O_5 over 50 cm plots at position 1 on Figure 6. If a minimium required mining thickness is 100 cm the grade becomes 11% P_2O_5 (position 2, Fig. 6)), or if a minimum of 200 cm is required, the grade drops to 5.5% P_2O_5 (position 3, Fig. 6).[12]

In Figure 6, a family of grade curves has been computed for various hypothetical ore zone thicknesses up to 2 m. The areas between the curves are separated into classes or domains bounded at the upper limit by lines at the 1 m and 2 m thickness values. These

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[11] Zones within a calculated ore sequence that were not sampled were assumed to be barren and set to zero. Weighted averages were determined as outlined by McKinstry (1957). Thicknesses presented are those associated with the calculated weighted average

[12] Exact formulae for determining these grades at different minimum thicknesses is as follows:
$y = a*b/x$, where
y - grade at a stipulated thickness (% P_2O_5)
x - stipulated minimum mining thickness (m)
a - raw grade value from outcrop (%P_2O_5)
b - raw thickness value from outcrop (m).

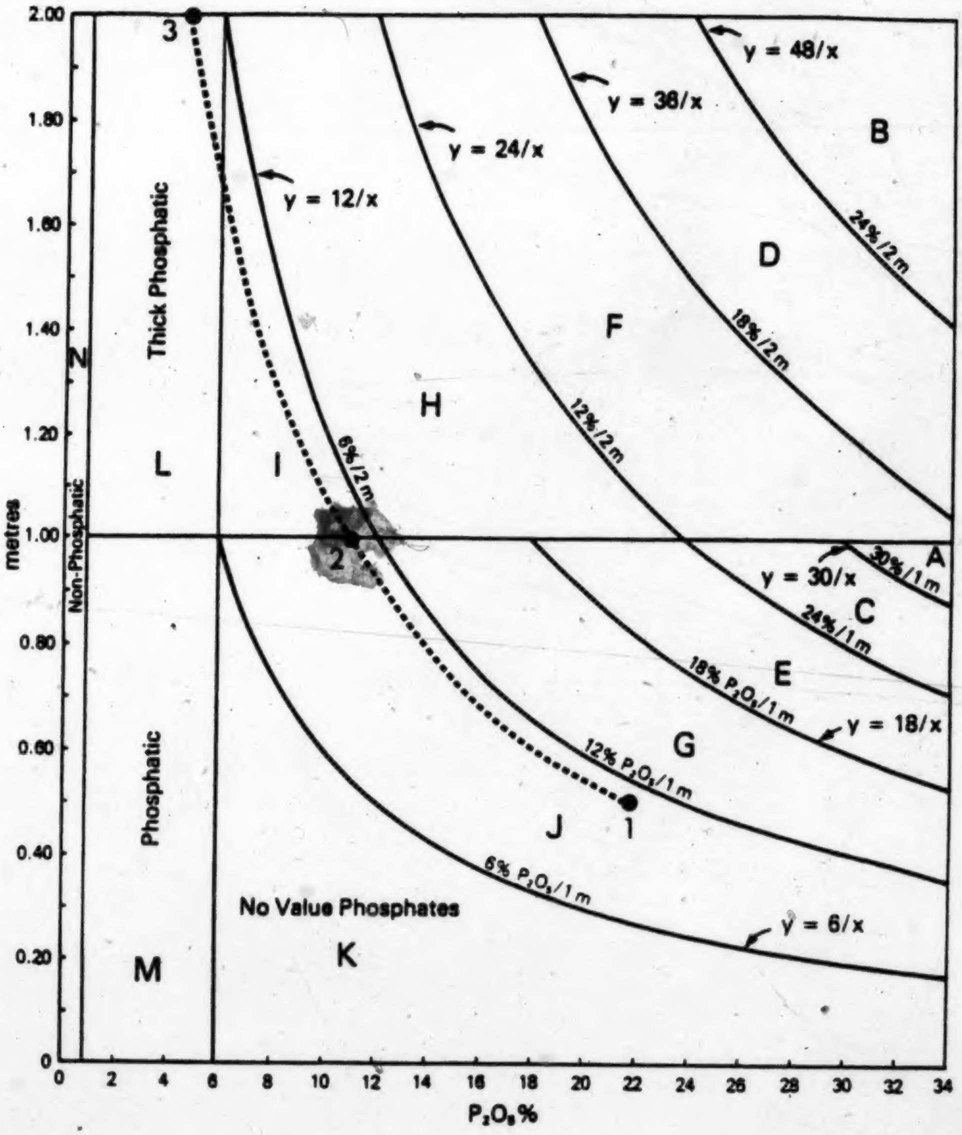

Figure 6. Economic classification of phosphate rocks

boundaries are based on the arbitrary selection of 1 m and 2 m as alternative minimum mining thicknesses for a phosphate ore body. Using these curves, any sample or series of samples from a stratigraphic section can be plotted and the expected grade quickly estimated. For example, point 1, Figure 6 plots within the J domain between the 6 and 12% P_2O_5 curves over 1 m. All grade / thickness values from each stratigraphic section can be grouped into one of the domains. This then leads to the second purpose for the classification scheme, which is to allow quick comparison of grade / thickness values on a regional basis, standardized to either 1 or 2 m minimum mining thickness, in order to locate those areas of highest potential. For example a region mapped as F has phosphate in the 12 to 18% P_2O_5 range over at least 2 m thickness and would have much better potential than a region mapped as K, having insufficient raw grade / thickness values to even reach the 6% curve.

This classification scheme is intended solely for comparison purposes within this study; widespread application of the scheme would require practical knowledge of a minimum mining thickness based on economic / technological considerations. A new family of grade curves could then be constructed and new domains assigned.

Exshaw Formation

Phosphatic rocks are found within four stratigraphic horizons in the Exshaw Formation: Upper phosphate horizon, Middle phosphate horizon, Lower phosphate horizon, and Basal Sandstone horizon (Fig. 7). The overall resource potential of the Exshaw Formation is shown on Figure 8.

The lower cherty black shale member, wherein most of the other horizons are found, is itself non-phosphatic. The average of all samples collected outside the phosphatic zones in this member is 0.16% P_2O_5 (n = 187, Std. Dev. = 0.1475). Several authors suggest a crustal average P_2O_5 content at about 0.27%. The LCBSM is therefore, below the crustal average, except for the phosphate-bearing horizons.

1. Upper Phosphate Horizon (UPH)

   The UPH within the Exshaw is found on the uppermost surface of the Upper Limestone Member, at the contact with the overlying Banff Formation. This horizon is usually expressed as a conglomeratic mixture of nodules, bone fragments, and a

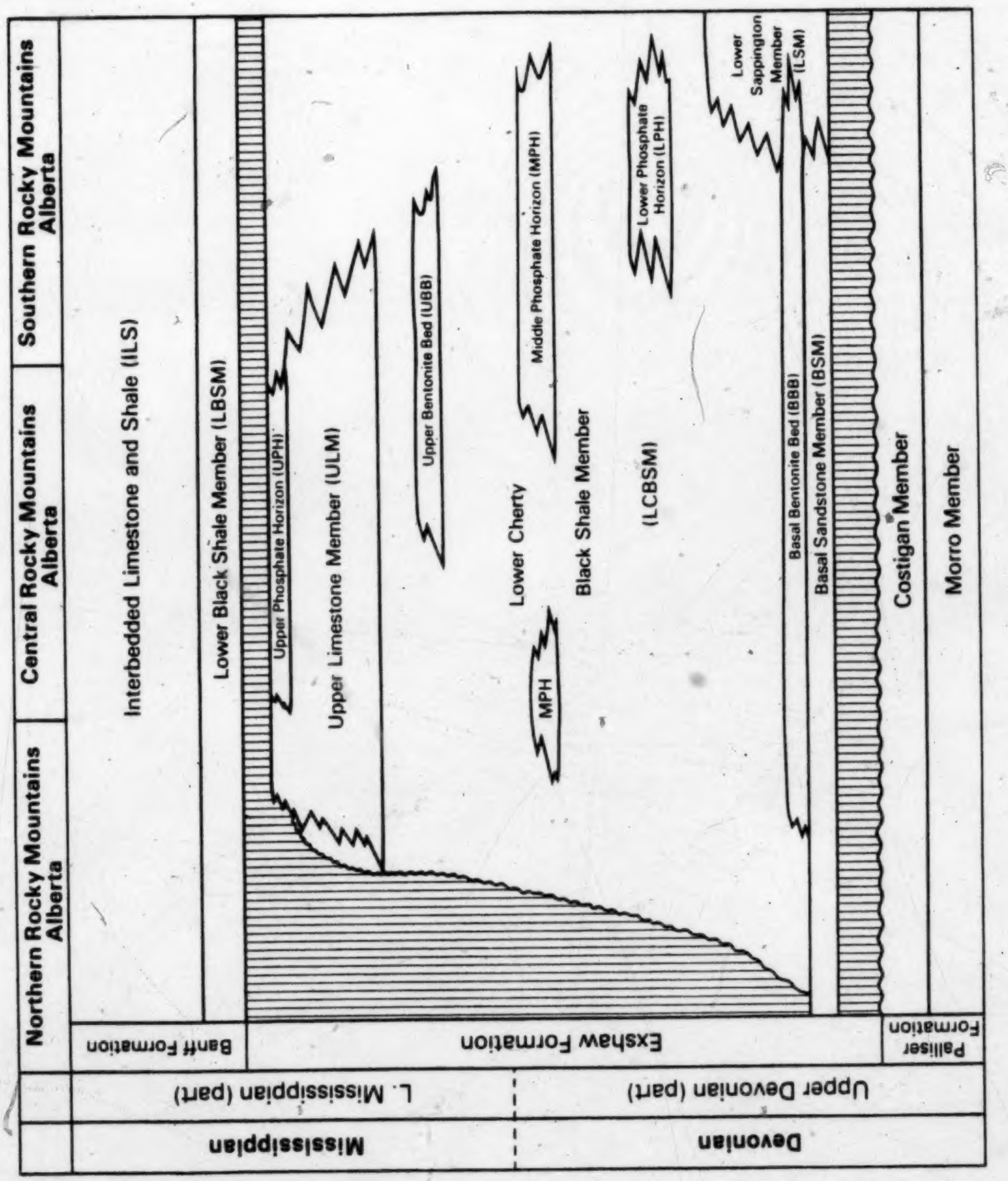
Northern Rocky Mountains Alberta
Central Rocky Mountains Alberta
Southern Rocky Mountains Alberta
Mississippian
Devonian
L. Mississippian (part)
Upper Devonian (part)
Banff Formation
Exshaw Formation
Palliser Formation
Interbedded Limestone and Shale (ILS)
Lower Black Shale Member (LBSM)
Upper Phosphate Horizon (UPH)
Upper Limestone Member (ULM)
Upper Bentonite Bed (UBB)
Middle Phosphate Horizon (MPH)
MPH
Lower Cherty
Black Shale Member
(LCBSM)
Lower Phosphate Horizon (LPH)
Lower Sappington Member (LSM)
Basal Bentonite Bed (BBB)
Basal Sandstone Member (BSM)
Costigan Member
Morro Member

Figure 7. Age, nomenclature and stratigraphic relations — Exshaw Formation

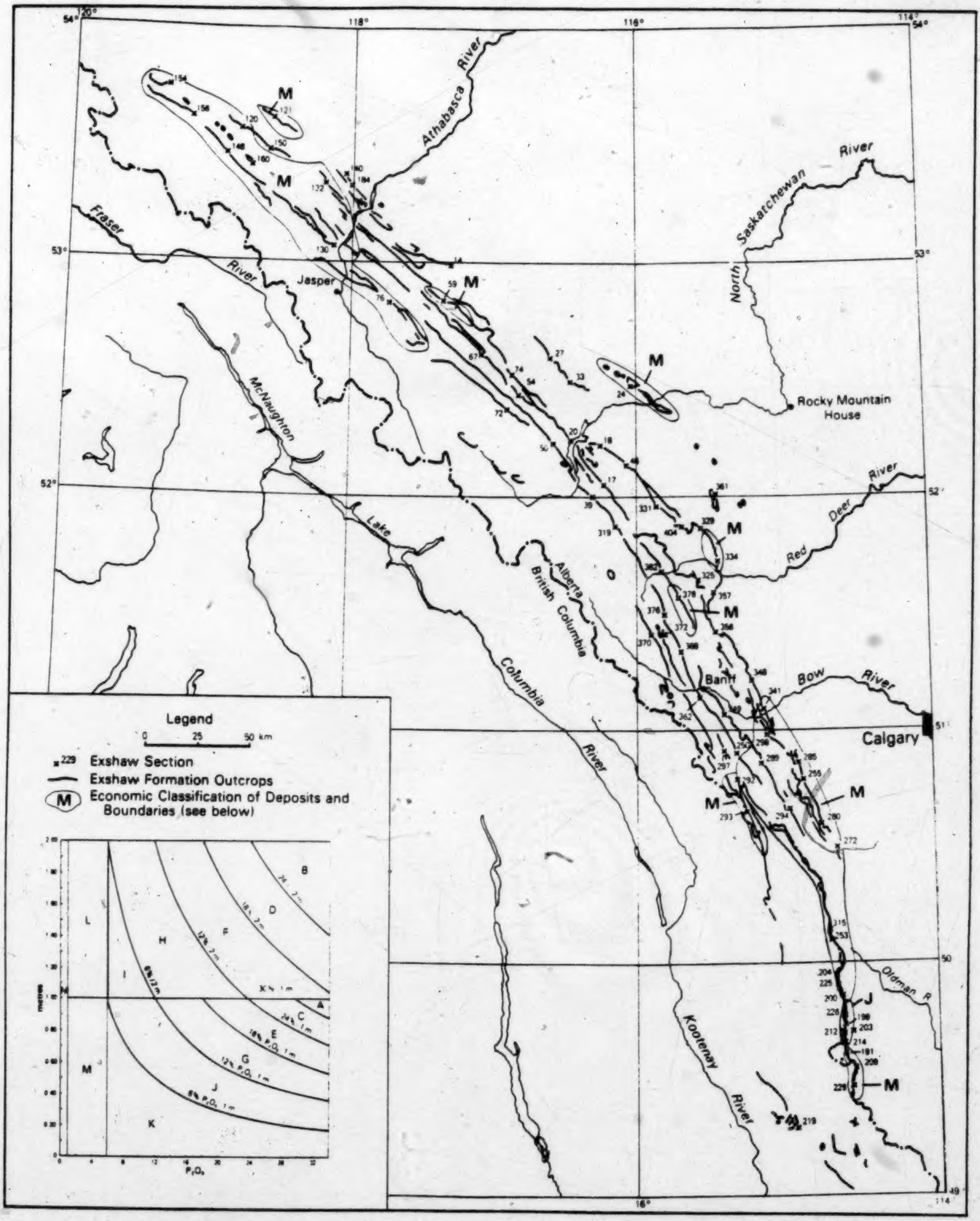
54°
120°
118°
116°
114°
53°
52°
51°
50
49°
Athabasca River
Fraser River
Jasper
North Saskatchewan River
Rocky Mountain House
Red Deer River
Bow River
Banff
Calgary
Oldman R.
Kootenay River
Columbia River
McNaughton Lake
Alberta
British Columbia
M
J
Legend
0 25 50 km
229 Exshaw Section
Exshaw Formation Outcrops
M Economic Classification of Deposits and Boundaries (see below)
metres
P2O5
B
D
F
H
L
I
A
C
E
G
J
K
M

Figure 8. Location of Exshaw Formation sections, outcrop locations, and phosphate potential

minor amount of pellets, intraclasts and ooids. The UPH has a very limited regional distribution, having been recognized only at sections 37, and 191 (Figure 8, Appendix 1).[13]. The P_2O_5 content of this horizon always exceeds 15%; however the associated thickness is always less than 10 cm. This horizon has no economic potential now or in the foreseeable future.

2. Lower and Middle Phosphate Horizons (LPH, MPH)

The LPH and MPH are located within the Lower Cherty Black Shale Member of the Exshaw (Fig. 7) and are confined largely to southwestern Alberta (Fig. 9). These two horizons are treated together, as they are usually separated by less than 2.0 m of shale, and if considered separately, would have little economic potential. Three occurrences of these horizons are known from the central and northern parts of the study area (sections 59, 24 and 382, Fig. 8); however only sections 59 and 293 have P_2O_5 values in the 1-3% range for a minimium 1 m thickness (Table 4). The LPH and MPH have their best development in the region north of Crowsnest Pass from Phillipps Pass to Racehorse Pass (Sections 226, 199, 214, Table 4).

In this region the grades are in the 6-10% P_2O_5 range for a minimum 1 m thickness. These horizons appear to drop in grade / thickness farther to the south (Sections 191 and 228; Table 4) with P_2O_5 values being in the 1-3% for a 1 m thickness. They also drop off in grade / thickness to the north.

The phosphate occurs as structureless, lensoidal and nucleated pellets interbedded with cherty shales. The structural / stratigraphic configuration of the Exshaw Formation is not a favorable one with respect to mining potential. Generally, the formation dips into the High Rock Range and has several hundred metres of Banff / Rundle Formation overlying (Fig. 5); open pit mining is therefore not feasable. Strip or slot-trench type mining may be possible within Phillipps, Deadman and Racehorse Passes. At these locations the Exshaw subcrops at low elevations, is in a structurally / stratigraphically more favorable positon, and dips moderately (20-45°) to the west. This same area, however, lies within the Eastern Slopes Management

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[13] The presence of the UPH, as herein defined, at section 191 is questionable. Macqueen and Sandberg (1970) do not consider the Upper Limestone Member, upon which the UPH sits, to be present at this locality. A phosphatic horizon nevertheless does exist at the top of the Exshaw at this locality, but may in fact belong to the Banff Formation

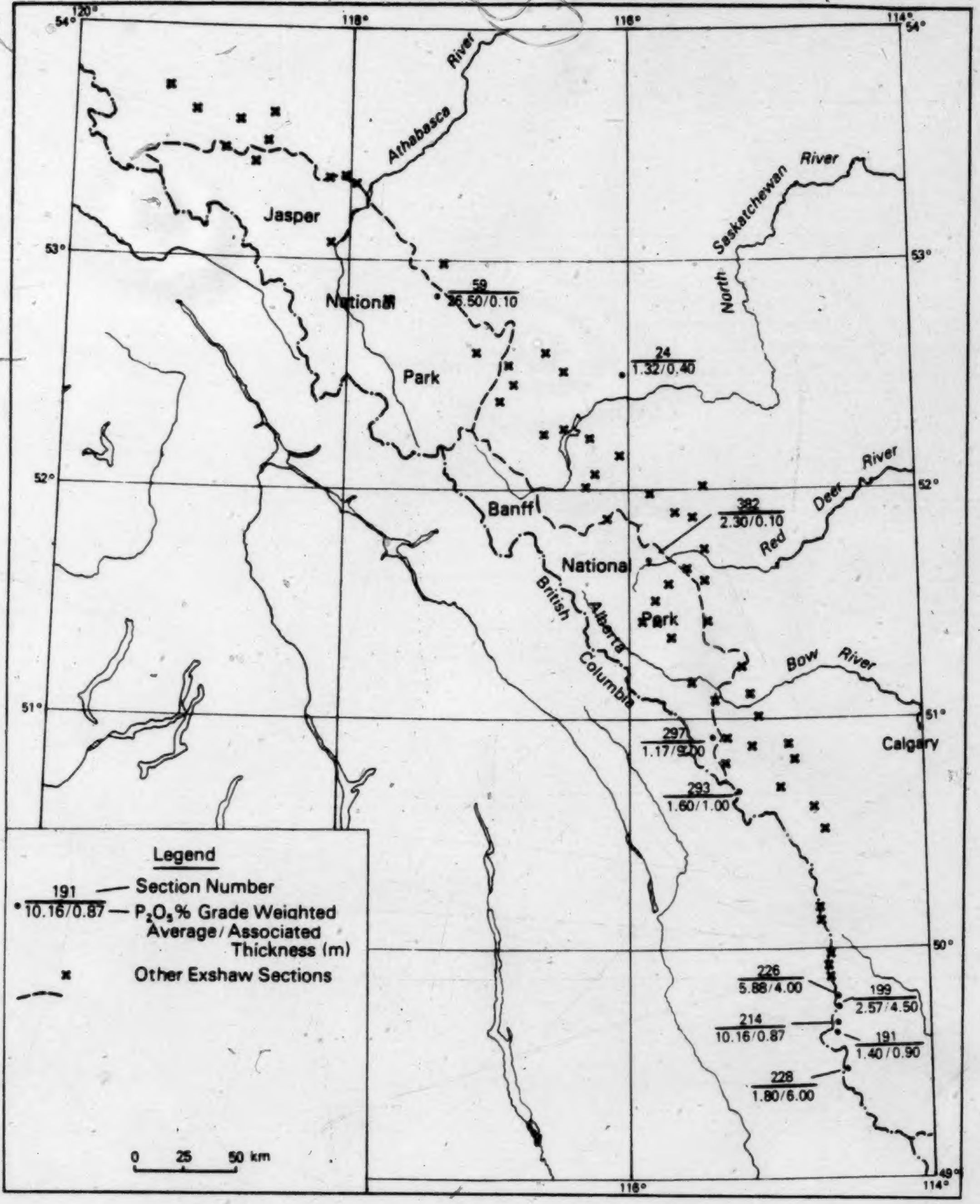
120°
54°
118°
116°
114°
54°
Athabasca
River
Jasper
National
Park
53°
53°
59
26.50/0.10
24
1.32/0.40
North
Saskatchewan
River
52°
52°
382
2.30/0.10
Red
Deer
River
Banff
National
Park
British
Columbia
Alberta
Bow
River
51°
51°
Calgary
297
1.17/9.00
293
1.60/1.00
50°
226
5.88/4.00
199
2.57/4.50
214
10.16/0.87
191
1.40/0.90
228
1.80/6.00
49°
116°
114°
Legend
191 — Section Number
10.16/0.87 — P₂O₅% Grade Weighted Average/Associated Thickness (m)
Other Exshaw Sections
0
25
50 km

Figure 9. Location, grade and thickness of Exshaw Formation — LPH and MPH phosphates

Table 4. Lithologic and Chemical Analysis Data - Middle and Lower Phosphate Horizons, Exshaw Formation.

SECTION	LITHOLOGY[@]	THICKNESS[#] (m)	WEIGHTED VALUES[?] P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N[*]	CLASS[!]
24	Ss;phost	0.30	1.33	320	66.3	0.40	0.20	2	M
59	Ss;pell	0.10	26.50	190	122.0	2.65	1.33	1	K
191	Mdst;phost	0.90	1.40	335	6.2	1.26	0.63	3	M
199	Sh;intbd	0.60	15.90	0	0.0	9.54	4.77	2	J
214	Sh;nod	0.87	10.16	0	0.0	8.84	4.42	3	J
226	Phos;	3.00	6.30	97	7.5	6.30	6.30	2	H
228	Sh;intbd	0.20	10.20	125	6.6	2.04	1.02	3	K
293	Sh;intbd	1.00	1.60	640	31.4	1.60	0.80	1	M
382	Ss;pell	0.10	2.30	130	151.0	0.23	0.12	1	M

[@] Lithology based on main lithology e.g. Ss;(sandstone) and phosphate modifer e.g. ;pell (phosphate pellets). Abbreviations: Ss - sandstone, Sh - shale, Mdst - mudstone, Phos - phosphate, Sltst - siltstone, Cgl - conglomerate, Ls - limestone, Dol - dolomite, phost - phosphatic, pell - pellets, intbd - interbedded phosphate, nod - nodules, cmt - cement, pbls - pebbles.

[#] Thicknesses are based on single or multiple horizons combined together.

[?] These values for P205 % , Vanadium, and Uranium are averages based on thickness weighting of individual horizons.

[*] Number of sampled horizons used to calculate the values.

[!] Economic classification of location based on Figure 6.

Policy Prime Protection area, i.e. no mineral development allowed (Fig. 1).

The resource potential of the MPH and LPH in the Crowsnest Pass area is estimated at between 1 and 10 million t (Table 13).

3. Basal Sandstone Horizon (BSH)

The BSH is a generally thin (<30 cm) sandstone, conglomerate, siltstone or more rarely shale, directly overlying the Palliser Formation (Fig. 7). This horizon is phosphatic in parts of the northern, south-central and southern regions (Fig. 10). Grades are in the 1.0 to 9.0% P_2O_5 range, with corresponding thicknessses in the 10 to 30 cm range (Table 5). The best grade / thickness combination is at Section 76 (Medicine Lake - 7.77% P_2O_5 / 45 cm). The phosphate occurs as bone conglomerates, pebbles, nodules, intraclasts, pellets, and occasionally as primary phosphate cement (microsphorite). This horizon has no foreseeable economic potential due to low grade / thickness combinations.

Rocky Mountain Supergroup

Phosphate is present, to some extent, in all of the formations of the Spray Lakes and Ishbel Groups (Fig. 11). Many of the phosphate horizons are found at disconformable contacts between the various formations and the problem of placing them in the correct time-stratigraphic position becomes difficult. This problem is compounded by varying depths of erosion and erosional truncations, by all of the formations thinning to the east, and by sparse fossil fauna evidence.

Spray Lakes Group

Tunnel Mountain Formation - Intraformational phosphates (TMI)

Phosphate occurs sporadically within the Tunnel Mountain Formation, although no continuous mappable zone could be identified. The phosphate occurs as reworked pebbles in a thin (<10 cm), predominantly chert pebble conglomerate or pebbly sandstone. Of the three occurrences known[14] only one grade / thickness determination is available. [15]The low grade and small thickness make the Tunnel Mountain Intraformational phosphates of little economic

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[14] Sections: 21, 48 and 281

[15] Section 21 - 1.22% P_2O_5/0.10 m

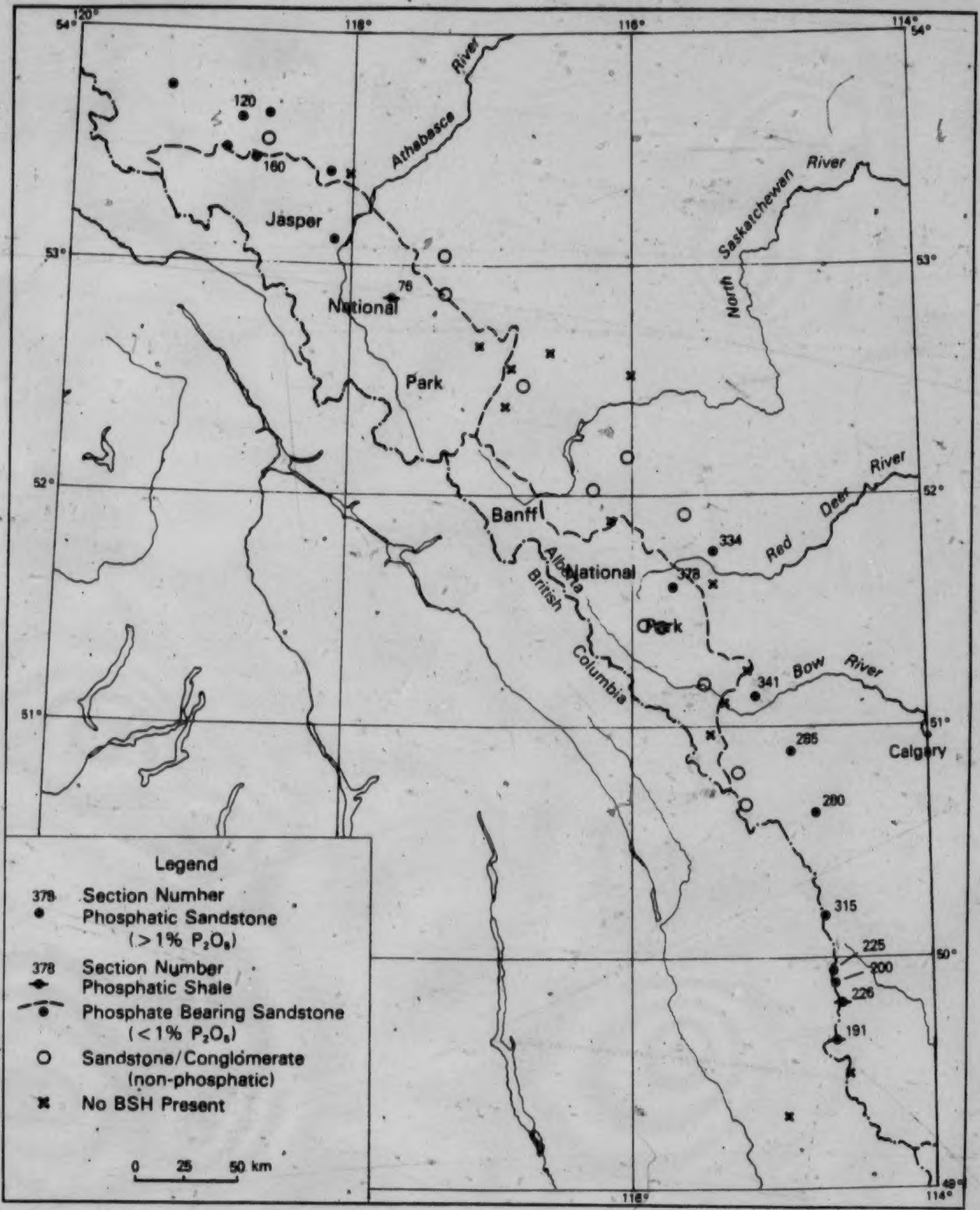
120°
54°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Athabasca River
North Saskatchewan River
Red Deer River
Bow River
Jasper
National
Park
Banff
National
Park
Alberta
British Columbia
Calgary
120
160
76
334
378
341
285
280
315
225
200
226
191
Legend
378 Section Number
Phosphatic Sandstone (>1% P2O5)
378 Section Number
Phosphatic Shale
Phosphate Bearing Sandstone (<1% P2O5)
Sandstone/Conglomerate (non-phosphatic)
No BSH Present
0 25 50 km

Figure 10. Location of basal sandstone horizon — Exshaw Formation

Table 5. Lithologic and Chemical Analysis Data - Basal Sandstone Member, Exshaw Formation.

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES						
			P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
76	Sh;pell,intbd	0.45	7.78	271	127.1	3.50	1.75	2	K
120	Ss;phost	0.10	4.10	110	13.0	0.41	0.21	1	M
160	Ss;cmt	0.10	4.50	60	13.0	0.45	0.23	1	M
191	Sh;intbd	0.30	4.00	2600	129.3	1.20	0.60	2	M
200	Ss;cmt	0.10	6.30	340	168.0	0.63	0.32	1	K
225	Ss;phost	0.03	8.67	400	80.0	0.26	0.13	1	K
226	Sh;phost	0.30	1.40	380		0.42	0.21	1	M
280	Ss;cmt	0.10	2.20	440	71.0	0.22	0.11	1	M
285	Ss;pell,cmt	0.10	1.90	120	34.0	0.19	0.10	1	M
315	Sh;intbd	0.25	2.96	212	74.4	0.74	0.37	1	M
334	Ss;cmt	0.10	3.70	60	53.0	0.37	0.19	1	M
341	Ss;nod,cmt	0.03	5.00	33	53.3	0.15	0.08	1	M
378	Ss;pell,phost	0.08	2.25	163	23.8	0.18	0.09	1	M

* N - number of samples

importance.

Tunnel Mountain Formation - Interformational phosphates (TIP)

The TIP consists of a conglomerate, pebbly or phosphatic sandstone bed composed of phosphate and chert pebbles (up to 2 cm), nodules, pellets and cement. It is commonly found directly overlying the Tunnel Mountain Formation (Fig. 11). The Tunnel Mountain is disconformably overlain by the Kananaskis Formation, except at Section 194 where it and the TIP are directly overlain by the Triassic-Sulphur Mountain Formation, and in the west side of the Elk Valley, British Columbia, where the Tunnel Mountain is overlain by the Johnston Canyon Formation.

Four of the nine known occurrences of the TIP zone are in the northern part of the Livingstone Range. The other three are in scattered locations as far north as the North Saskatchewan River area.[16]

This TIP zone varies from 0.01 to 1.50 metres thick, and has a phosphate content ranging from 0.08 to 8.90% P_2O_5. Table 6 summarizes the analytical data available on this zone.

No economic potential is foreseen for this zone as thickness/grade combinations never reach an acceptable level.

Kananaskis Formation-Intraformational phosphates (KFIP)

Phosphate occurs sporadically within the Kananaskis Formation with a slight tendency to be found near the top. The phosphate is expressed as patchy cement in sandstones and quartzites and less commonly as reworked pebbles within conglomerates. Four occurrences from the southern and central regions are known[17]. Table 7 provides details of grade/thickness, lithology, etc. Section 210, near Tent Mountain in the Crowsnest Pass, is worthy of mention, as here the grade/thickness is 8.40%P_2O_5/ 1.0 metres.

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[16] Sections 194, 264, 266, and 267 in the Livingstone Range and Sections 206, 230, 232, 38 and 395 in scattered locations.
[17] Sections 210, 267, 332, and 381

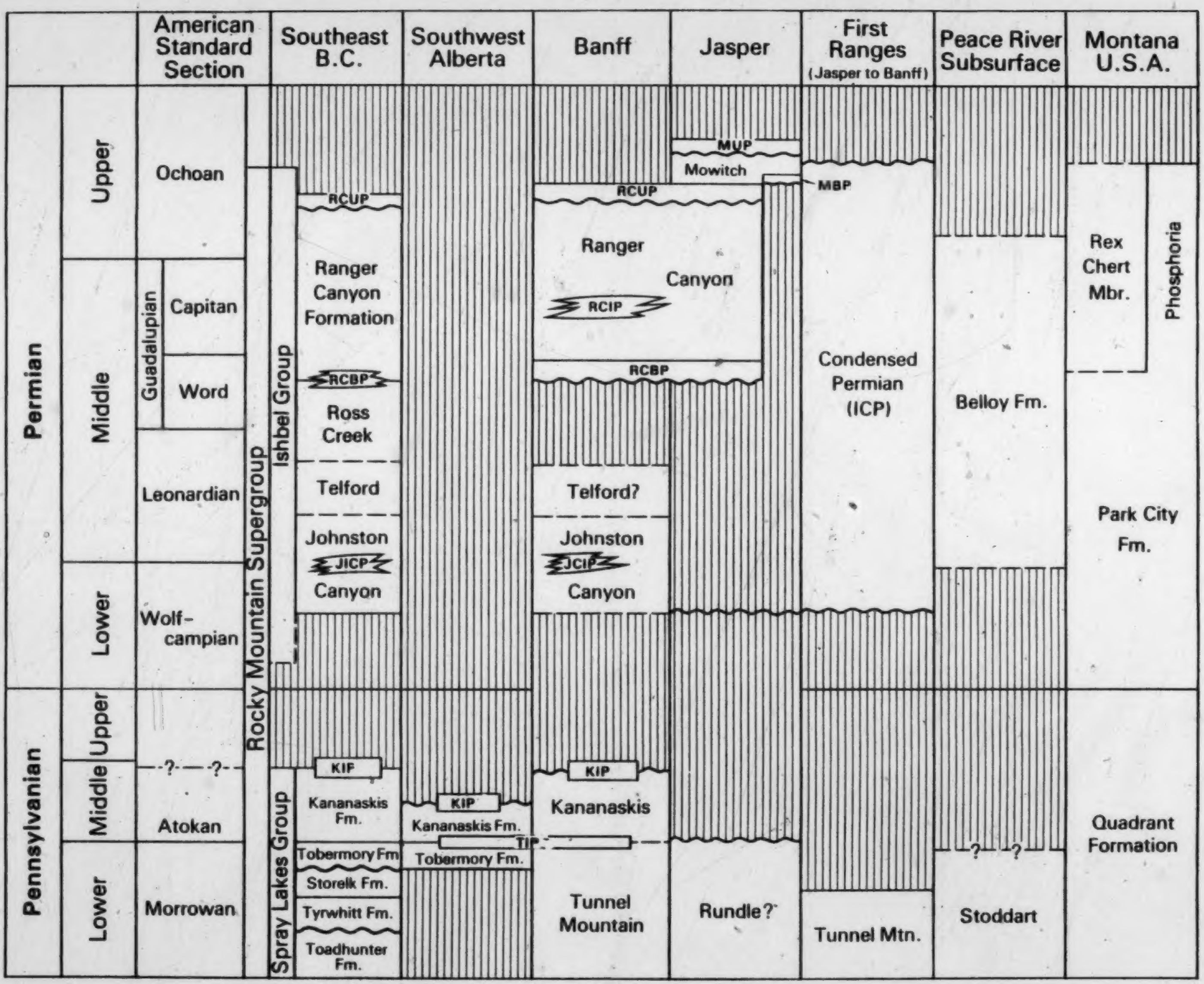
American Standard Section
Southeast B.C.
Southwest Alberta
Banff
Jasper
First Ranges (Jasper to Banff)
Peace River Subsurface
Montana U.S.A.
Permian
Pennsylvanian
Upper
Middle
Lower
Upper
Middle
Lower
Ochoan
Guadalupian
Capitan
Word
Leonardian
Wolf-campian
?—?
Atokan
Morrowan
Rocky Mountain Supergroup
Ishbel Group
Spray Lakes Group
RCUP
Ranger Canyon Formation
RCBP
Ross Creek
Telford
Johnston
JICP
Canyon
KIF
Kananaskis Fm.
Tobermory Fm
Storelk Fm.
Tyrwhitt Fm.
Toadhunter Fm.
KIP
Kananaskis Fm.
TIP
Tobermory Fm.
RCUP
Ranger
Canyon
RCIP
RCBP
Telford?
Johnston
JCIP
Canyon
KIP
Kananaskis
Tunnel Mountain
MUP
Mowitch
Rundle?
MBP
Condensed Permian (ICP)
Tunnel Mtn.
Belloy Fm.
?
?
Stoddart
Rex Chert Mbr.
Phosphoria
Park City Fm.
Quadrant Formation

Figure 11. Nomenclature and stratigraphic correlation chart of the Rocky Mountain Supergroup, Alberta, British Columbia and Montana

Table 6. Lithologic and Chemical Analysis Data - Tunnel Mountain Interformational Phosphate (TIP).

			WEIGHTED VALUES						
SECTION	LITHOLOGY	THICKNESS (m)	P_2O_5%	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5% (1 m.)	P_2O_5% (2 m.)	N*	CLASS
38	Cgl;pbls,cmt	1.50	1.73	40	4.8	1.73	1.30	1	L
194	Ss;pell,nod	0.20	6.00	50	38.0	1.20	0.60	1	K
206	Cgl;	0.01	0.08	20	5.3			1	N
232	Cgl	0.20						1	
264	Cgl;pbls	0.05	9.00	40	12.0	0.45	0.22	1	K
266	Cgl;phost	0.61						1	
267	Ss;pbls	0.05	4.20	60	12.0	0.21	0.10	1	M
276	Cgl;pell,nod	0.10	13.90	50	28.0	1.39	0.69	1	K
317	Cgl	1.00						1	
395	Cgl;pell	0.50						1	

* Number of Samples

Kananaskis Formation Interformational phosphates (KIP)

A chert breccio-conglomerate is found at the top of the Kananaskis Formation (Fig. 11) over a wide geographic area (Fig. 12). This conglomerate is generally cemented with phosphate and / or contains reworked phosphate pebbles. The Johnston Canyon Formation disconformably overlies this zone in all areas. Figure 12 shows the location of phosphate-bearing outcrops of the KIP zone, and Table 8 summarizes all available lithological and chemical analysis data.

Section 281 - Mist Mountain contains greater than 9% P_2O_5 for a 1 m thickness, and may be of economic interest (Fig. 12, Table 8). More detailed sampling is necessary to evaluate the potential of this zone.

Ishbel Group

Johnston Canyon Formation-Intraformational Phosphate (JCIP)

Phosphate within the Permian Johnston Canyon Formation is found within the formation as pellets and nodules in a series of interbedded siltstones, sandstones and shales (Fig. 11). This zone has a limited lateral distribution, being confined to the area south of Banff and mainly in the westernmost sections (Fig. 13). Sections 365 (Mt Ishbel), 229 (Lizard Range), 231 (Weight Creek) and 221 M(t. Broadwood) all have phosphate grades greater than 13% P_2O_5 for a minimum 1 m thickness (Table 9). Low grade phosphatic rocks and a number of unassayed nodule zones (1-6% P_2O_5) exist in the Kananaskis area (Section 306, 307, and 308).

The region around Mt. Broadwood, Lizard Range, and the Weight Creek-Brule Creek (Area I and II, Fig. 13) areas would seem to have the best potential for phosphate exploitation, within the JCIP zone (Table 9). Extensive, as yet untested, outcrops of Johnston Canyon Formation are likely present to the southeast of Mt. Broadwood into the Wigwam River-Macdonald Range area. This area may show further extension of the JCIP zone.

Table 7. Lithologic and Chemical Analysis Data - Kananaskis Formation, Intraformational Phosphate (KFIP).

			WEIGHTED VALUES						
SECTION	LITHOLOGY	THICKNESS (m)	P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
210	Qzt;cmt	1.00	8.40	140	53.4	8.40	4.20	1	J
267	Ss;cmt	2.00	3.80	70	12.5	3.80	3.80	1	L
332	Ss;	8.00	1.30	40	1.4	1.30	1.30	1	L
381	Cht;pell,pbls	0.40	4.20	30	4.0	1.68	0.84	1	M

* Number of Samples

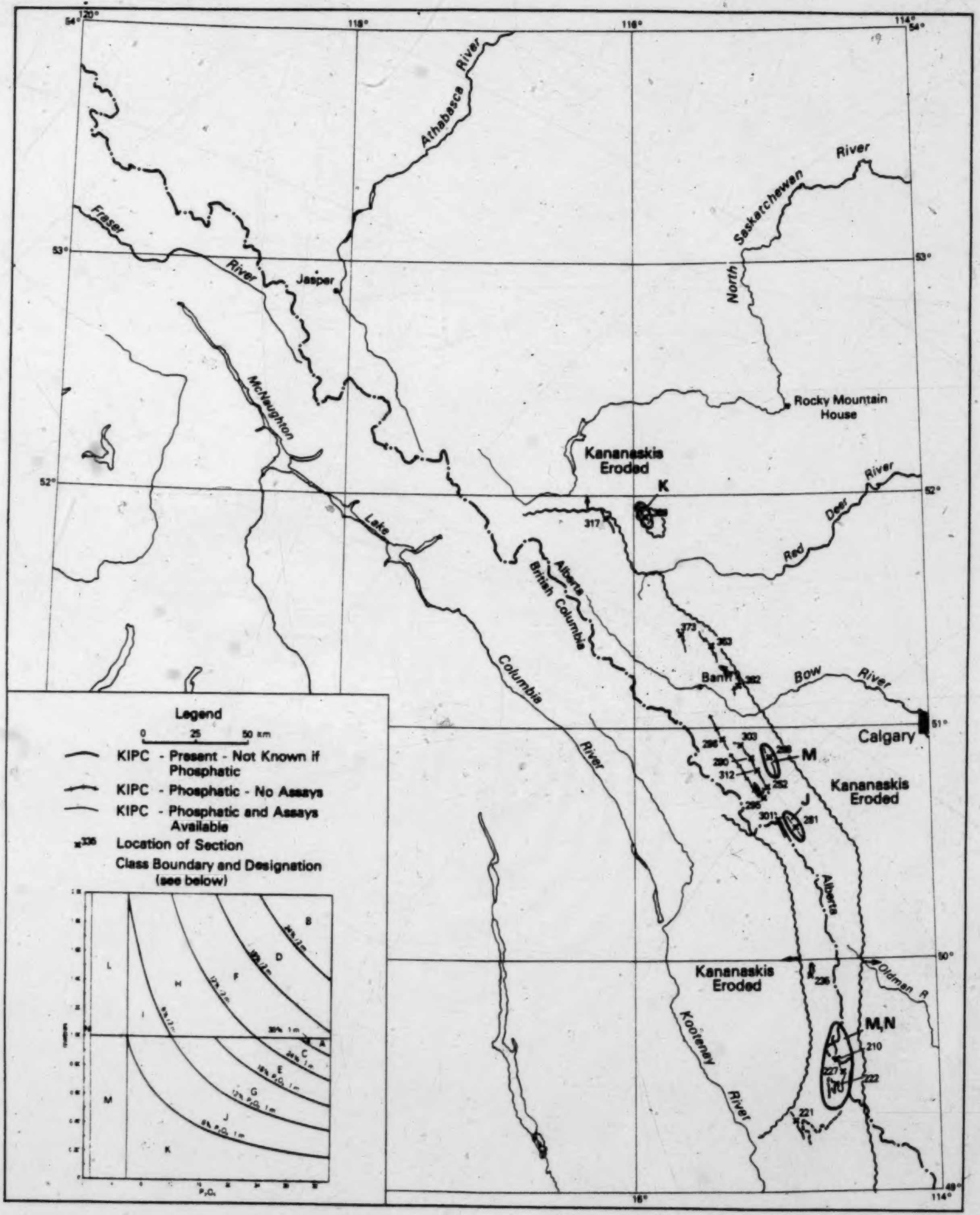
120°
54°
118°
116°
114°
54°
53°
52°
51°
50°
49°
114°
116°
Athabasca River
Fraser River
Jasper
North Saskatchewan River
Rocky Mountain House
McNaughton Lake
Kananaskis Eroded
K
317
Red Deer River
Alberta
British Columbia
Columbia River
373
353
Banff
332
Bow River
Calgary
298
303
299
M
290
312
252
295
J
301
281
Kananaskis Eroded
Alberta
Kananaskis Eroded
236
Oldman R
Kootenay River
M,N
210
227
222
221
Legend
0
25
50 km
KIPC - Present - Not Known if Phosphatic
KIPC - Phosphatic - No Assays
KIPC - Phosphatic and Assays Available
x336 Location of Section
Class Boundary and Designation (see below)
A
B
C
D
E
F
G
H
I
J
K
L
M
N
24% / 2 m
18% / 2 m
12% / 2 m
6% / 2 m
30% 1 m
24% 1 m
18% P2O5 1 m
12% P2O5 1 m
6% P2O5 1 m
P2O5

Figure 12. Kananaskis interformational phosphate conglomerate — Location of outcrops and sections

Table 8. Lithologic and Chemical Analysis Data - Kananaskis Formation, Interformational Phosphate . (KIP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
210	Cgl;cmt	2.00	0.72	30	3.3	0.72	0.72	2	N
221	Cgl	0.30						1	
222	Ss;nod	0.75	4.10	33	35.7	3.08	1.54	3	M
227	Ss;nod	0.98	29.27$					1	
235	Cgl;cmt	0.20						1	
252	Cgl	0.10	0.20	40	4.0	0.02	0.01	1	N
281	Ss;cmt	1.10	9.33	57	33.7	9.33	5.13	2	J
288	Sltst;cmt	0.80	3.90	50	26.1	3.12	1.56	2	M
295	Ss;cmt,pell	0.40	3.40	20	13.5	1.36	0.68	1	M
301	Cgl	0.30						1	
303	Ss;phost	3.66						1	
312	Cgl;cmt	0.10						1	
353	Cgl;nod	0.50						1	
373	Cgl;cmt	0.60	0.71	30	5.1	0.43	0.21	2	
389	Cgl;cmt	0.30	13.80	30	10.0	4.14	2.07	1	K
392	Ss	0.50						2	

Cht-chert, ?-phoshate present; type uncertain

$ Assay based on nodules only.

* Number of Samples.

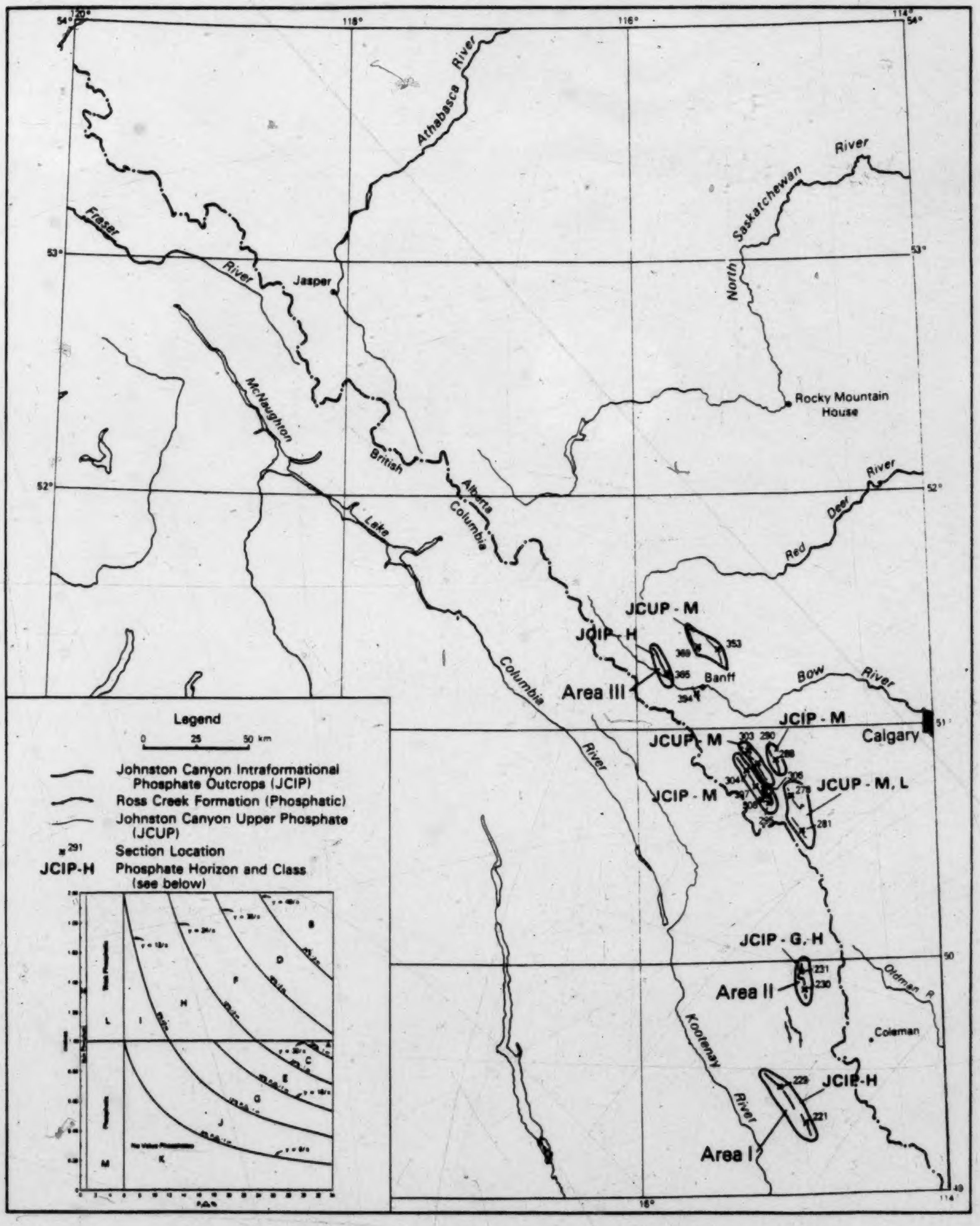
54°
120°
118°
116°
114°
54°
Athabasca River
Fraser River
Jasper
53°
53°
North Saskatchewan River
Rocky Mountain House
McNaughton Lake
British Columbia
Alberta
52°
52°
Red Deer River
JCUP - M
JCIP - H
369
353
365
Area III
Banff
394
Bow River
Columbia River
JCIP - M
Calgary
51°
JCUP - M
303
290
288
305
304
307
306
295
278
281
JCIP - M
JCUP - M, L
JCIP - G, H
231
230
Area II
50
Oldman R.
Coleman
Kootenay River
229
JCIP-H
221
Area I
49
118°
114°
Legend
0
25
50 km
Johnston Canyon Intraformational Phosphate Outcrops (JCIP)
Ross Creek Formation (Phosphatic)
Johnston Canyon Upper Phosphate (JCUP)
291
Section Location
JCIP-H
Phosphate Horizon and Class (see below)
A
B
C
D
E
F
G
H
I
J
K
L
M

Figure 13. Johnston Canyon and Ross Creek Formations — Phosphate bearing outcrops and classes of deposits

Table 9. Lithologic and Chemical Analysis Data - Johnston Canyon Formation Intraformational Phosphate (JCIP) and Upper Phosphate (JCUP).

SECTION	LITHOLOGY	THICKNESS (METRES)	WEIGHTED VALUES P_2O_5 % (RAW)	WEIGHTED VALUES VANADIUM (PPM)	WEIGHTED VALUES URANIUM (PPM)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N	CLASS
221	Ss;nod,pell	7.90	4.86	42 (6-147)	12.0 (9.2-47.2)	15.60$ (1.5 m.)	9.71$ (2.5 m.)	9	H
229	Phos;cmt,pell	4.08	8.57			16.69$	8.57	5	H
229$	Phos;cmt,pell	0.83	20.10						G(best)$
230	Phos;intbd,pell	1.83	7.18			7.18	6.57	4	H
231	Phos;pell	0.94	16.86			15.85	7.92	3	G
288	Ss;pell	0.10	4.90	170	41.0	0.49	0.24	1	M
295	Sltst;nod,pell	1.60	1.66	3	1.8	1.66	1.33	2	L
295$	Sltst;pell,nod	0.20	5.90	20	14.9			1	M(best)$
304	Ss;nod	0.23	30.00?					1	
306	Ss;nod	0.10						1	
307	Ss;nod	0.30						1	
308	Ss;nod	0.61						1	
365	Ss;pell	3.51	7.77			7.77	7.77	2	H
365$	Sltst;pell,nod	1.08	13.73			13.73	7.44		H
394	Sh;intbd	0.03	30.66			0.92	0.46	1	K
278*	Ss;cmt	1.50	2.59	100	6.3	2.59	1.94	1	L
281*	Ss;cmt	0.90	1.93	55	9.1	1.74	0.87	3	M
290*	Ss;cmt, nod	0.35	4.42	82	18.5	1.55	0.77	3	M
303*	Ss;nod	0.33	30.00			9.90	4.95	1	M
304*	Ss;nod	0.41						1	
353*	Ss;cmt, nod	0.60	2.36	76	5.6	1.42	0.71	2	M
369*	Ss;cmt	0.50	3.90	180	24.2	1.95	0.97	1	M

* Johnston Canyon Upper Phosphate (JCUP) all others Johnston Canyon Intraformational Phosphate (JCIP).

$ Recalculated from original data.

? Assay based on nodules only.

Johnston Canyon Formation-Upper Phosphate (JCUP)

The JCUP zone occurs at the top of the Johnston Canyon Formation in those areas where younger Permian strata have been removed, leaving the Johnston Canyon in direct contact with the Triassic Sulphur Mountain Formation. The zone is expressed as slightly phosphatic cemented sandstones, and sandstones containing phosphate nodules. While individual nodules may assay quite high (Section 303, Table 9) the overall grade of the nodule-bearing zone is low (Class M, 1-6% P_2O_5).

This zone has only been recognized in the Banff and Kananaskis areas (Fig. 13) and may in fact be equivalent to the RCBP horizon discussed in a later section. The JCUP zone is not considered to be of any economic value at the present time.

Ross Creek Formation

The Ross Creek Formation is only exposed in the Telford Thrust Sheet, west of the Elk Valley, in the Fernie Basin area between Fernie and Latitude 50° (Fig. 13) (McRae and McGugan, 1977). Phosphate nodules and pellets have been reported from this formation (McRae and McGugan, 1977); however, no analytical data are available and the phosphate potential is still largely unknown.

Ranger Canyon Formation-Basal phosphate zone (RCBP)

One of the most widespread phosphate-bearing stratigraphic zones in Alberta is the RCBP. This horizon is found directly below the massive, cliff forming Ranger Canyon Formation (Fig. 11), and it extends from Willmore Wilderness Park south to the Fernie Basin area (Fig. 14). However, many of the easternmost exposures of the Ranger Canyon Formation are not phosphatic at this stratigraphic position (Fig. 15). Grade / thickness combinations, in general, improve in an east to west manner (Fig. 16). However, this generality is breached in three locations: northern Jasper Park-Willmore Wilderness Park, southern Jasper Park-North Saskatchewan River, and the Crowsnest Pass area. In these localities, better grade / thickness or Class of deposits exist for the eastern localities. (see Appendix 3 for all grade / thickness values).

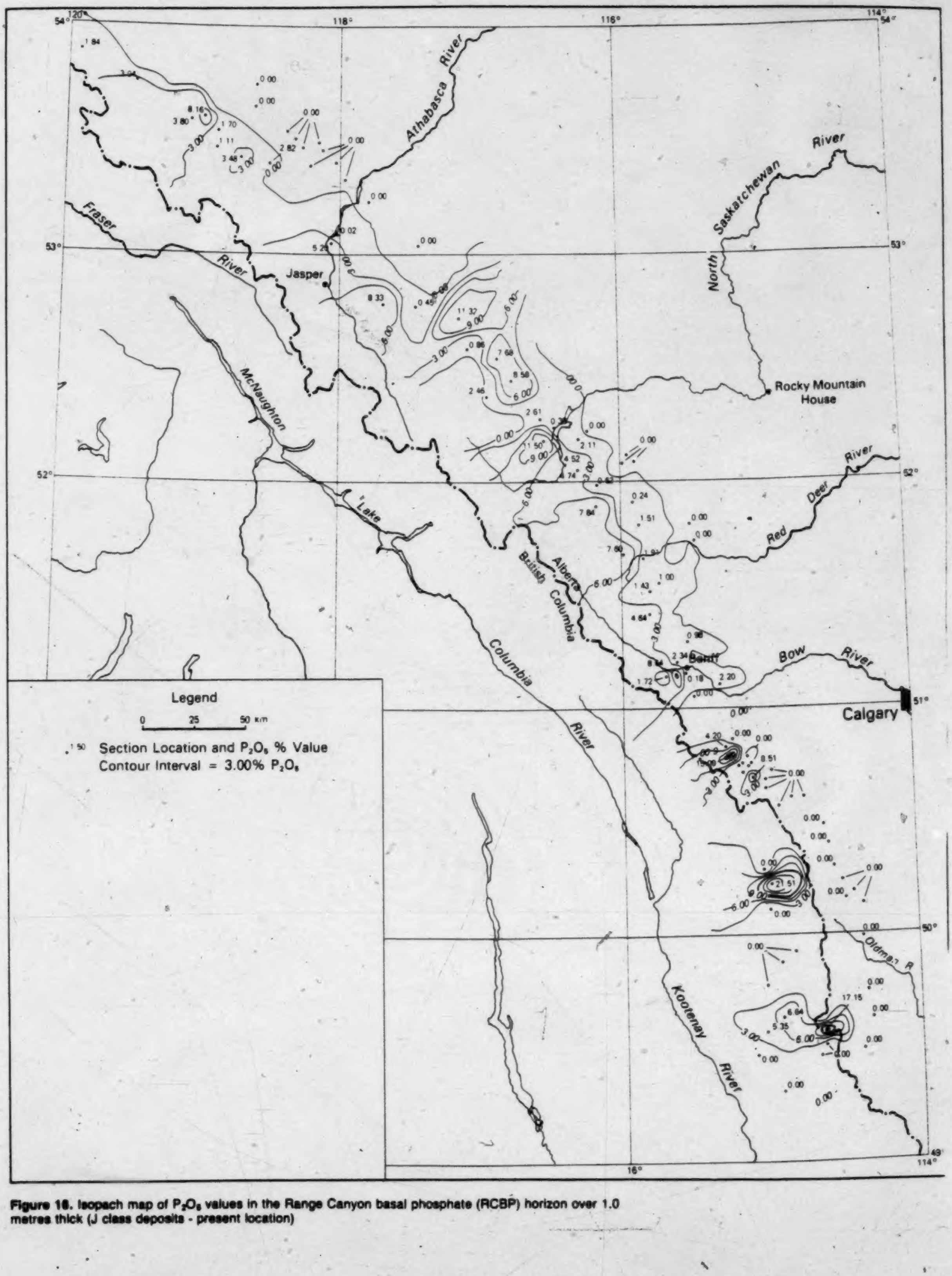
Legend
0 25 50 km
.1.50 Section Location and P_2O_5 % Value
Contour Interval = 3.00% P_2O_5
120°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Athabasca River
Fraser River
North Saskatchewan River
Red Deer River
Bow River
Oldman R
Columbia River
Kootenay River
McNaughton Lake
Jasper
Banff
Calgary
Rocky Mountain House
Alberta
British Columbia
21.51
17.15
11.32
11.50
3.00
6.00
9.00

Figure 18. Isopach map of P_2O_5 values in the Range Canyon basal phosphate (RCBP) horizon over 1.0 metres thick (J class deposits - present location)

In terms of future development potential of this horizon, four localities are worthy of mention (Fig. 14):

1) West Central Willmore Wilderness Park - most localities are Class K with one locality up to a Class J (6-12% P_2O_5 / 1 metre).

2) North Saskatchewan River - one area south and one north of the North Saskatchewan River are in the J Class of deposits. Most other RCBP exposures in this area between the National Parks are in the K Class.

3) Crowsnest Pass Area - a single section (210) in this area showed phosphate in the Class F category (12-18% P_2O_5 for a 2 m thickness, at the RCBP horizon. However, as all of the Permian is condensed in this area to about 3 metres, there is some doubt as to whether this showing does in fact belong to the RCBP horizon. The anomalous thickness at this location[11] suggests that the phosphate was deposited in a preexisting channel and does not represent a typical thickness for this area. This idea is supported by sections north and south of Section 210 that show a much lesser thickness.

4) Southeastern British Columbia, Telford Creek area - A single section (232) in the Telford Thrust Sheet showed phosphate deposits at the RCBP in the J Class. The aerial extent shown on Figure 14 is somewhat uncertain and is based on thickness (but not grades) given by McRae and McGugan (1977). The RCBP horizon may be present along the west side of the Elk Valley, northward toward Kananaskis Park; however, such an occurrence is not known.

The phosphate in the RCBP zone is expressed in most areas as a cement binding a chert breccia or conglomerate. The phosphate is also found cementing siltstone or fine grained quartzose sandstones (Plate 6F). In the band of J Class deposits along the southern boundary of Jasper Park and into the

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[11] This is the thickest section of RCBP ever observed by this author

North Saskatchewan River area (Fig. 14), the phosphate is expressed as reworked phosphate pebbles in a medium to coarse grained sand matrix (Plate 2D) as well as the previously described cement. In all cases the phosphate is dark black in color. The zone also shows anamolously high radiation readings with a radiation detection device.

Ranger Canyon Formation Intraformational Phosphate Zone (RCIP)

Phosphate is known from within the Ranger Canyon Formation at four localities in and around the western portions of Banff National Park (Fig. 15). The phosphate invariably occurs within a sandstone lithology as cement, phosphatic debris or nodules.[19] All occurrences in the in the M or L Class (Table 10) and are of no economic interest.

Ranger Canyon Upper Phosphate Zone (RCUP)

Phosphate is located at the unconformable contact between the Ranger Canyon Formation and the overlying Sulphur Mountain Triassic Formation. This phosphate occurrence has a wide areal distribution extending from Willmore Wilderness Park to southeastern British Columbia.

Grade / thickness combinations within this zone are not well developed with only one locality, Section 363 (Fig. 15), attaining a Class J status (>6.0% P_2O_5 for a minimum 1 m thickness). Moreover, this locality is in Banff National Park. Nodule-bearing sandstone with high individual nodule assays are present in the Kananaskis area (Section 304, 305, Appendix 4), but the overall bed Class designation is as yet undetermined. All other occurrences of this zone are in the M, N, or K Classes.

The RCUP horizon is usually expressed as a phosphate cemented chert pebble conglomerate, as reworked phosphate pebble conglomerate, phosphate-cemented sandstone or nodule-bearing sandstone. It represents an erosional surface of unknown duration.

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[19] The Ranger Canyon Formation is overwhelmingly almost always chert, with sandstone being a minor component.

Table 10. Lithologic and Chemical Analysis Data - Ranger Canyon Formation Intraformational Phosphate (RCIP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5%	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
38	Ss,phost	5.30	1.00	60	1.6	1.00	1.00	1	L
332	Ss,cmt	0.90	3.30	60	5.8	2.97	1.48	1	M
342	Ss,phost	1.50	1.80	60	14.6	1.80	1.35	1	M
371	Ss,nod	0.40	0.15	60	7.5				

* Number of Samples

Mowitch Formation Basal Phosphate (MBP)

A phosphate pebble, or phosphate-cemented chert pebble conglomerate occurs at the base of the Mowitch Formation in three localities within Willmore Wilderness Park (Sections 97, 116 and 117, Fig. 15). In all three localities the Mowitch Formation directly and disconformably overlies Carboniferous age carbonates. This zone may be equivalent to any, some, or all of the unconformity-type phosphate zones previously discussed (RCUP, RCBP, JCUP, etc).

All of the showings of this zone are M or K Class (6% P_2O_5 for a 1 m thickness) and are of no economic significance (Appendix 4).

Mowitch Formation Intraformational Phosphate Zone (MIP)

The Mowitch Formation is known to be slightly phosphatic and in two localities (Sections 146 and 151) north of Jasper National Park the phosphatic zones reach a K or M Class (less than 6% P_2O_5 over 1 metre, Table 11). The phosphate occurs as patchy cement within the predominant sandstone lithology and also as cement within intraformational conglomerates.

Mowitch Formation Upper Phosphate (MUP)

Six localities in the northern and central regions have a phosphate pebble conglomerate at the contact between the Mowitch and the Triassic, Sulphur Mountain Formation (Table 11). Although most P_2O_5 values for this horizon exceed 10%, corresponding thicknesses seldom exceed 20 cm (Table 11). Most showings are therefore in the M or K Class, and of little economic importance.

Ishbel Condensed Phosphate (ICP)

In the easternmost Front Ranges and Foothills regions, the entire Permian, and occasionally part of the Pennsylvanian, are reduced to a thin (< 1 m) chert-carbonate conglomerate. This conglomerate locally contains phosphate pebbles and phosphate cement. Ten stratigraphic sections of the condensed Permian conglomerate examined in this study have Class M or K type phosphates (Fig. 6) associated with them (Table 12). P_2O_5 contents range

Table 11. Lithologic and Chemical Analysis Data - Mowitch Formation Upper Phosphate (MUP) and Mowitch Formation Intraformational Phosphate (MIP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES			P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
			P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)				
421	Cgl;pbls	1.52						1	
38	Ss;nod,cmt	0.10	10.40	110	31.0	1.04	0.52	1	K
57	Cgl;cmt	0.20	2.10	80	14.5	0.42	0.21	1	M
61	Ss	0.20						2	
116	Ss;pbls	0.10	18.60	210	45.0	1.86	0.93	1	K
133	Cgl;pbls	0.15	20.80	120	30.6	3.12	1.56	1	K
138	Cgl;pbls	0.20	12.70	170	22.5	2.54	1.27	1	K
146•	Cgl;cmt	0.20	16.80	130	26.5	3.36	1.68	1	K
151•	Ss;?	10.50	5.10	40	5.6	5.10	5.10	1	M

* Number of Samples

• Sections of Mowitch Formation Interformational Phosphate (MIP).

from 2 to 14%, however, thicknesses rarely exceed 0.5 m.

Resource Evaluation

Estimates of the amount of phosphate available in Permian-Pennsylvanian formations within the study area were made for areas deemed to contain J Class deposits or better. The procedure used to derive these estimates is outlined in Appendix 6. The JCIP and RCBP are the only two horizons known that meet these qualifications (Table 13). Based on the present data, there is estimated to be a maximum of 334 million t of in situ Permian phosphate rocks, mostly in the low grade/thin J Class (6-12% P_2O_5 for a minimum 1 m thickness). Thirty-one percent (31%) of this in situ resource lies in areas politically amenable to exploitation with 90% (of the 31%) in the Fernie Basin area (B.C.) and 10% within Alberta. Of the remaining 69% found in restricted land use areas, 46% (of the 69%) lies in the Eastern Slopes Prime Protection Zone of Alberta, 14% in Kananaskis Provincial Park and 40% within Banff and Jasper National Parks.

Spray River Group

Phosphate rocks within the Triassic Spray River Group are largely confined to the various members of the Sulphur Mountain Formation, although minor occurrences are also known from most members of the Whitehorse Formation (Fig. 17). The members with the best economic potential are: the Whistler, (in the Cline-North Saskatchewan Rivers area), and the Llama (in the Kananaskis Range). Both members have at the stated localities weighted P_2O_5% contents in the 2-6% range for a minimum 1 m thickness.

Basal Phroso Member Phosphate (BPMP)

The BPMP is situated at the disconformable erosional contact of the Phroso Member and the underlying strata which are variable from Permian to Mississippian in age. Gibson (1974) describes this zone as "a cherty, quartzose, phosphatic pebble-conglomerate, ranging in thickness from a few inches to 1 foot". This pebble-conglomerate may however be more properly part of the Permian-Pennsylvanian depositional cycle which was dealt with in the previous

Table 12. Lithologic and Chemical Analysis Data – Ishbel Condensed Phosphate (ICP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
8	Cgl;pbls	0.20	3.55	40	15.0	0.71	0.35	1	M
95	Cgl;pbls	0.50	3.80	80	7.4	1.90	0.95	1	M
105	Cgl;pbls,cmt	0.10	11.30	140	13.0	1.13	0.56	1	K
185	Cgl;cmt	0.07	5.28	114	7.1	0.37	0.18	1	M
186	Qzt	0.39	4.74			1.85	0.92	3	M
187	Cht;nod	0.09	14.55			1.31	0.65	1	K
264	Ss;pbls	0.35	3.20	20	7.4	1.12	0.56	1	M
267	Ss;pbls	0.10	4.70	40	8.0	0.47	0.23	1	M
271	Cht;phost	2.00	2.00	25	2.8	2.00	2.00	1	M
302	Ss;nod	0.10						1	

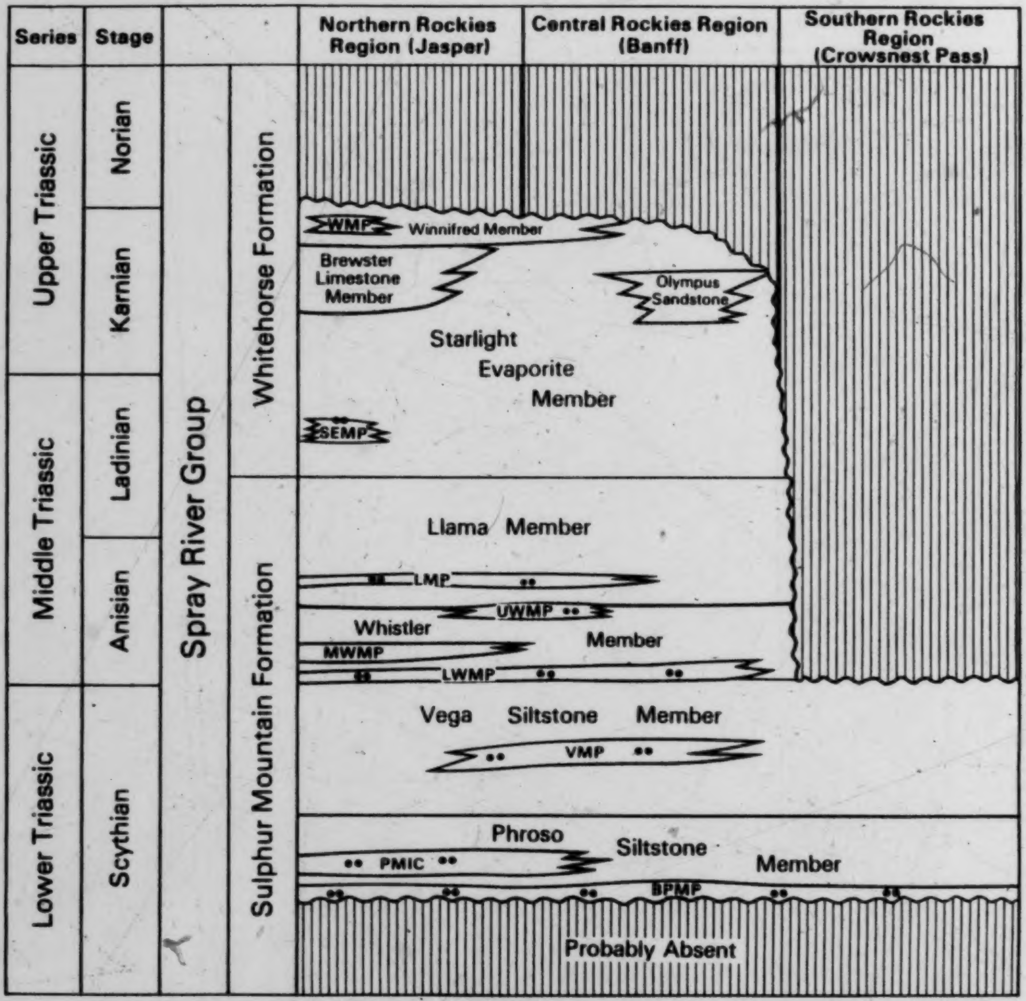
* Number of Samples

Table 13. Summary of Phosphate in Situ Resource Present - Exshaw Formation and Ishbel Group.

HORIZON	AREA	GEOGRAPHICAL SITUATION*	CLASS AVERAGE	OUTCROP LENGTH (KM)	ASSUMED DOWNDIP PROJECTION DISTANCES 300 m $(t \times 10^6)$	50 m $(t \times 10^6)$	N#
JCIP	I - Fig. 13	FB-BC	H	35	56.1	9.3	2
JCIP	II - Fig. 13	FB-BC	G-H (1 m)	20	16.0	2.7	2
JCIP	III - Fig. 13	BNF-Alta	H	17	27.2	4.5	1
TOTAL JNCP					99.3	16.5	
RCBP	II - Fig. 14	FB-BC	J	26	20.1	3.5	1
RCBP	I - Fig. 14	DP-Alta	F (2m)	6	9.6	1.6	1
RCBP	III - FIG. 14	KNP-Alta	J	40	32.1	5.3	2
RCBP	IV - South-Fig. 14	BNP-Alta	J	40	32.1	5.3	1
RCBP	IV - North-Fig. 14	PPZ-Alta	J	21	16.8	2.8	1
RCBP	V - South-Fig. 14	PPZ-Alta	J	114	91.4	15.2	4
RCBP	V - North-Fig. 14	JNP-Alta	J	40	32.1	5.3	2
TOTAL RCBP					234.2	39.0	
PERMIAN PHOSPHATE TOTALS					333.5	55.5	
Exshaw	Crowsnest Pass	PPZ	J	13.3	10.4	1.7	3

*Abbreviations Used: FB - Fernie Basin, BNF - Banff National Park, DP - Development Permitted in Alberta,
KNP - Kananaskis Provincial Park, PPZ - Prime Protection Zone, Alberta,
JNP - Jasper National Park

Number of stratigraphic data points used in calculating area


Series
Stage
Northern Rockies Region (Jasper)
Central Rockies Region (Banff)
Southern Rockies Region (Crowsnest Pass)
Upper Triassic
Middle Triassic
Lower Triassic
Norian
Karnian
Ladinian
Anisian
Scythian
Spray River Group
Whitehorse Formation
Sulphur Mountain Formation
WMP
Winnifred Member
Brewster Limestone Member
Olympus Sandstone
Starlight Evaporite Member
SEMP
Llama Member
LMP
UWMP
Whistler Member
MWMP
LWMP
Vega Siltstone Member
VMP
Phroso Siltstone Member
PMIC
BPMP
Probably Absent

Phosphatic Horizon (••)

BPMP - Basal Phroso Member Phosphate
PMIC - Phroso Member (Intraformational Conglomerate)
VMP - Vega Member Phosphate
LWMP - Lower Whistler Member Phosphate
MWMP - Middle Whistler Member Phosphate
LMP - Llama Member Phosphate
UWMP - Upper Whistler Member Phosphate
WMP - Winnifred Member Phosphate
SEMP - Starlight Evaporite Member Phosphate

Figure 17. Nomenclature and stratigraphic correlation of the Spray River Group, Front Ranges of Alberta (modified from Gibson, 1974.)

section. Gibson (1965, 1968a, 1968b, and 1974), however, reports four localities [20] that contain this phosphatic conglomerate and which he believes belong to the Sulphur Mountain Formation. No assay results are available. None of the sections examined by the present author showed a conglomerate that could definitely be associated with the Triassic.

The lower 1 to 20 m of the Phroso Member consist of a series of very argillaceous, recessive-weathering, organic-rich siltstones. These beds were investigated for their phosphate potential and are also included in the BPMP horizon. Of six sections examined (96, 99, 192, 211, 241 and 391, Fig. 18) representing the entire study area, only section 211 showed anomalously high P_2O_5 values [21] The BPMP, as herein defined to be part of the Sulphur Mountain Formation, appears to be of no economic value with respect to phosphate.

Phroso Member Intraformational Conglomerates (PMIC)

Intraformational conglomerates consisting of reworked phosphate pebbles and shell beds are found sporadically within the Phroso Member (Sections 32, 147, 172, and 189). Sections 32 and 189 both lie in the easternmost Front Ranges, or outliers thereof, and both were sampled. Two horizons at Section 32 contain phosphatic material; an upper one consisting of a 5-cm phosphate pebble bed (not sampled), and a lower one consisting of a 10-cm phosphatic shell horizon assaying 18.90% P_2O_5. Section 189 contained a single 5-cm phosphate pebble conglomerate bed which assayed 2.00% P_2O_5. The PMIC horizon seems to be confined to the northern and north-central Rockies and is not a continuous mappable horizon. It has no economic significance.

Vega Member Phosphate (VMP)

Phosphate is found in the Vega Member primarily as fish debris and secondarily as scattered reworked pebbles. Showings are not confined to any one zone, and have been reported by Gibson (1965, 1968a, 1968b, and 1974) from twelve sections throughout the northern and southern parts of the study area (Fig.

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[20] Sections 83, 167, 170 and 403; Fig. 18, Appendix 1

[21] 1.40%/2.00 m, average = 0.27% for this recessive horizon

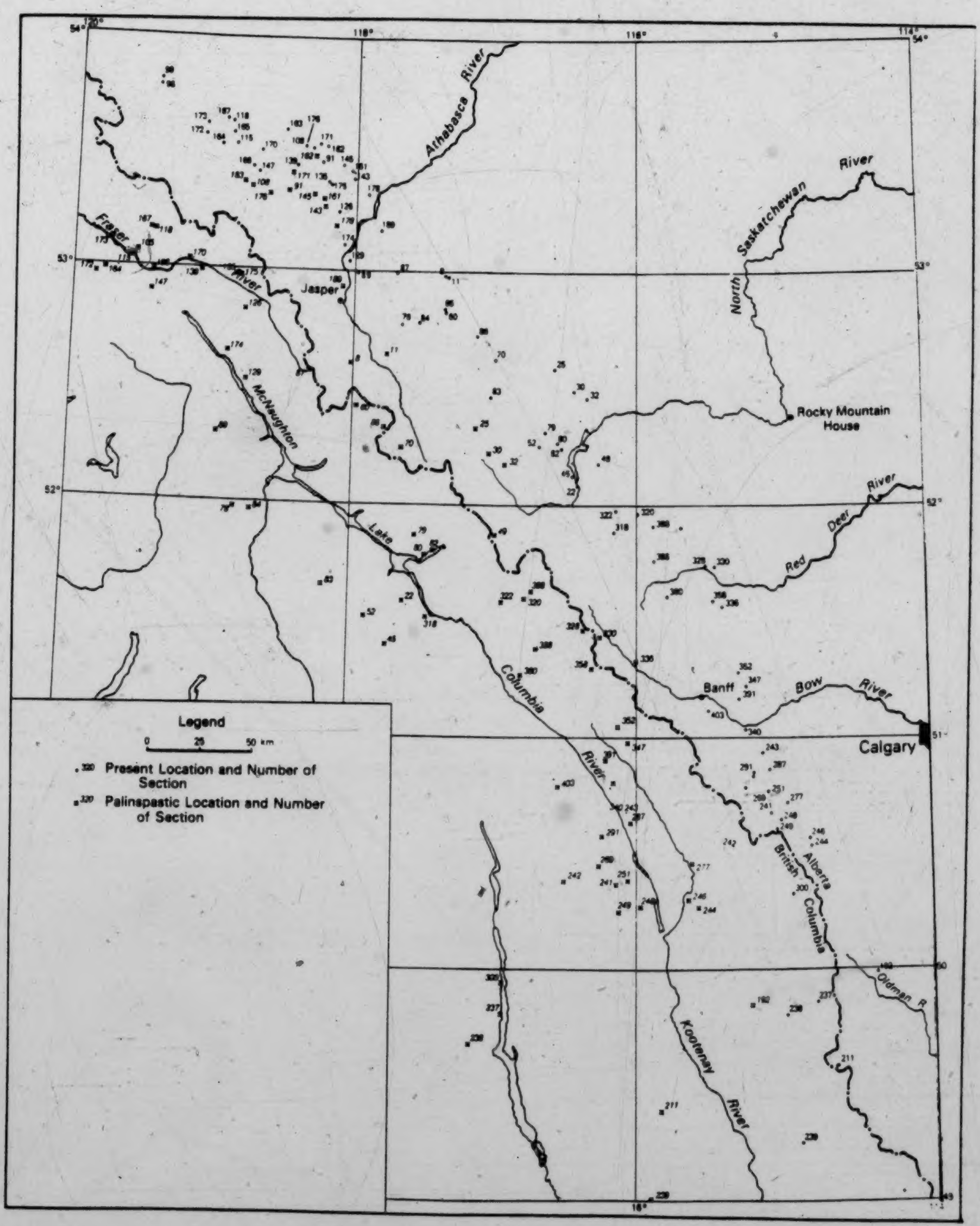
54°
120°
118°
116°
114°
53°
52°
51°
50
49
Athabasca River
Fraser River
Jasper
McNaughton Lake
North Saskatchewan River
Rocky Mountain House
Red Deer River
Bow River
Banff
Calgary
Columbia River
Kootenay River
British Columbia
Alberta
Oldman R.
Legend
0 25 50 km
• 320 Present Location and Number of Section
▪ 320 Palinspastic Location and Number of Section

Figure 18. Present and palinspastically restored positions of Spray River Group (Triassic) stratigraphic sections studied and Spray River Group outcrops

18).[22] No analyses are available. Most occurrences are less than 5 cm thick, and the VMP is therefore of no economic importance.

Whistler Member Phosphate

Phosphate within the Whistler Member is concentrated at the top and bottom of the member. The lower zone (LWMP) has been reported over an area from Willmore Wilderness Park as far south as the Red Deer River. Most occurrences of the upper zone (UWMP) are found around the North Saskatchewan River valley. The phosphate zones to be seems present only in the more westerly sections examined of the Whistler Member. A third, middle zone is present in a few sections. All of the analytical data for the Whistler Member phosphate is summarized in Table 14.

Upper Whistler Member Phosphate

Three sections showed significant phosphate results within the UWMP (Sections 79, 52, and 45; Table 14). All of these sections are in the Cline-North Saskatchewan River area (Fig. 18) and the UWMP horizon seems to increase in grade and thickness to the west. Two other localities (Sections 99 and 380, Fig. 18) north and south of the Cline-Saskatchewan River valley, have some minor amounts of phosphate (Table 14). The phosphate within the UWMP is present mainly as quartz-cored pellets and intraclasts in a dolomite cement, with some quartz / feldspar matrix.

The UWMP horizon seems to have its best economic potential in the Cline-North Saskatchewan Rivers area, where up to 50 cm of 10.40% P_2O_5 is present (Section 45).

Middle Whistler Member Phosphate (MWMP)

This phosphate zone has been identified at Section 126, in the Snake Indian River area, Jasper National Park , and possibly from Sections 79, 80 and 82 in the Cline-North Saskatchewan River area.[23] The MWMP has very limited

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[22] Sections: 83, 84, 167, 170, 172, 174, 238, 244, 246, 249, 251, and 269. Appendix 1

[23] These three sections were reported by Hudson Bay Oil and Gas during a phosphate exploration program in 1965. Precise stratigraphic details are not available, but a middle zone is alluded to.

Table 14. Lithologic and Chemical Analysis Data - Whistler Member Phosphate

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
UWMP†									
45	Sltst;nod	0.50	10.40	382	35.3	5.20	2.60	2	K
52	Ss;pell	0.60	2.67	60	17.5	1.60	0.80	1	M
99	Cgl;phost	0.02	1.24	83	3.3	0.02	0.01	2	M
380	Sltst;pell	0.50	0.89	68	4.8	0.44	0.22	1	N
MWMP									
126	Cgl;pell	0.05	6.20	289	19.0	0.31	0.16	2	K
LWMP									
22	Sltst;phost	7.00	1.12	40	2.2	1.12	1.12	1	M
83	Sltst;phost	2.40	-	-	-	-	-	-	-
84	Dol;phost	5.00	-	-	-	-	-	-	-
164	Cgl;phost,pbls	0.30	-	-	-	-	-	1	-
166	Cgl;phost	0.30	-	-	-	-	-	1	-
172	Sltst;phost	2.40	-	-	-	-	-	1	-
174	Phos;pell	0.20	-	-	-	-	-	1	-
318	Sltst;pell	0.30	0.90	50	5.7	0.27	0.14	1	N
WMU									
79	Phos;pell	0.47	-	-	-	-	-	-	-
80	Sh;pell	3.65	5.90	-	-	5.90	5.90	1	L
82	Ls;pell	0.91	-	-	-	-	-	-	-
147	Sltst;phost	0.04	0.32	840	8.4	0.01	-	1	N
386	Phos;pell	0.20	25.40	40	18.0	5.08	2.54	1	K

* N - number of samples

† UWMP - upper whistler member phosphate, MWMP - middle whistler member phosphate, LWMP - lower whistler member phosphate, WMU - whistler member undifferentiated phosphate.

economic potential by itself; however in combination with the upper or lower zones in a continuous sequence, it may have some value.

Lower Whistler Member Phosphate (LWMP)

The LWMP zone is known to be present from Willmore Wilderness Park as far south as the Red Deer River (Fig. 18, Table 14). Although the LWMP zone has a larger regional extent than the other Whistler phosphatic zones, it seems to lack significant grades and/or thicknesses. Section 174, Mount Greenock, has the thickest exposure of phosphate rock (20 cm); however, no analyses are available. The phosphate potential of the LWMP is still uncertain, but does not seem promising.

Whistler Member Undifferentiated (WMU)

Phosphate in this generalized zone is for phosphatic zones within sections of reduced Whistler Member and for phosphates of uncertain stratigraphic positions, reported by several oil company reports (Hudson Bay Oil and Gas, 1965; Mobil Oil, 1966). Section 80 - Cline-North Saskatchewan River area, Table 14 - seems to have some potential, with the entire Whistler Member estimated to average 5.90% P_2O_5 over 3.65 m (Hudson's Bay Oil and Gas, 1965).

Llama Member Phosphate (LMP)

Phosphate in the Llama Member is concentrated in the lower, and to a lesser extent, the upper portions of the member. The phosphate is normally expressed as fossil shell remains and also as pebbles. These phosphate are rarely found within a single bed but are scattered throughout several metres of strata. One exception seems to be in the Kananaskis Range (Section 242, Appendix 1) where concentrated phosphate pellet beds are interbedded with non-phosphatic sandstones over a 2.35 m interval (weighted P_2O_5 average = 1.56%). Only two of the phosphatic beds were sampled (Mobil Oil Canada, 1966), yielding weighted grade/thicknesses of 5.2% P_2O_5 over 0.7 m or 3.67% P_2O_5/ 1.0 m. Many other beds in this 2.35 m interval are described as containing phosphate pellets and more detailed sampling may yield better grade/thickness values. The LMP zone is found throughout the Kananaskis

Range where twenty other occurrences have been reported[24] by Gibson (1965, 1968a, 1968b, 1974). However no assay results are available and all occurrences are considered insignificant.

Starlight Evaporite Member Phosphate (SEMP)

Nine phosphate locations are known from within the Starlight Evaporite Member of the Whitehorse Formation[25]. All occurrencs are as phosphatic *Lingula* shell remains, found scattered throughout the member, confined to the NTS area "83E" (Northern Rockies) and none are of any economic significance[26].

Winnifred Member Phosphate (WMP)

Phosphate is found in the Winnifred Member at six localities, all within the Northern Rockies region[27]. All of the occurrences are thin and lenticular, composed of phosphatic shell remains (lingulid) and scattered pellets. None are of any economic significance.

Fernie Group

Phosphate in the Jurassic Fernie Group is best developed within the Nordegg Member and Nordegg equivalent (Fig. 19). Phosphate is also present, to a lesser extent, within the Rock Creek Member. Minor phosphate occurrences, with respect to quality and aerial distribution, are found in the Red Deer Member and the Poker Chip Shales [28].

Average phosphate, vanadium and uranium values for all the Members and Beds of the Fernie Group are given in Table 15. These values exclude all phosphatic zones and are included for comparative purposes to illustrate "normal" values for the members and beds. Phosphate within the Upper and Middle Fernie is consistently between 0.20 and 0.29 P_2O_5% with a higher range of values (0.38-0.71 P_2O_5%) in the Lower Fernie.

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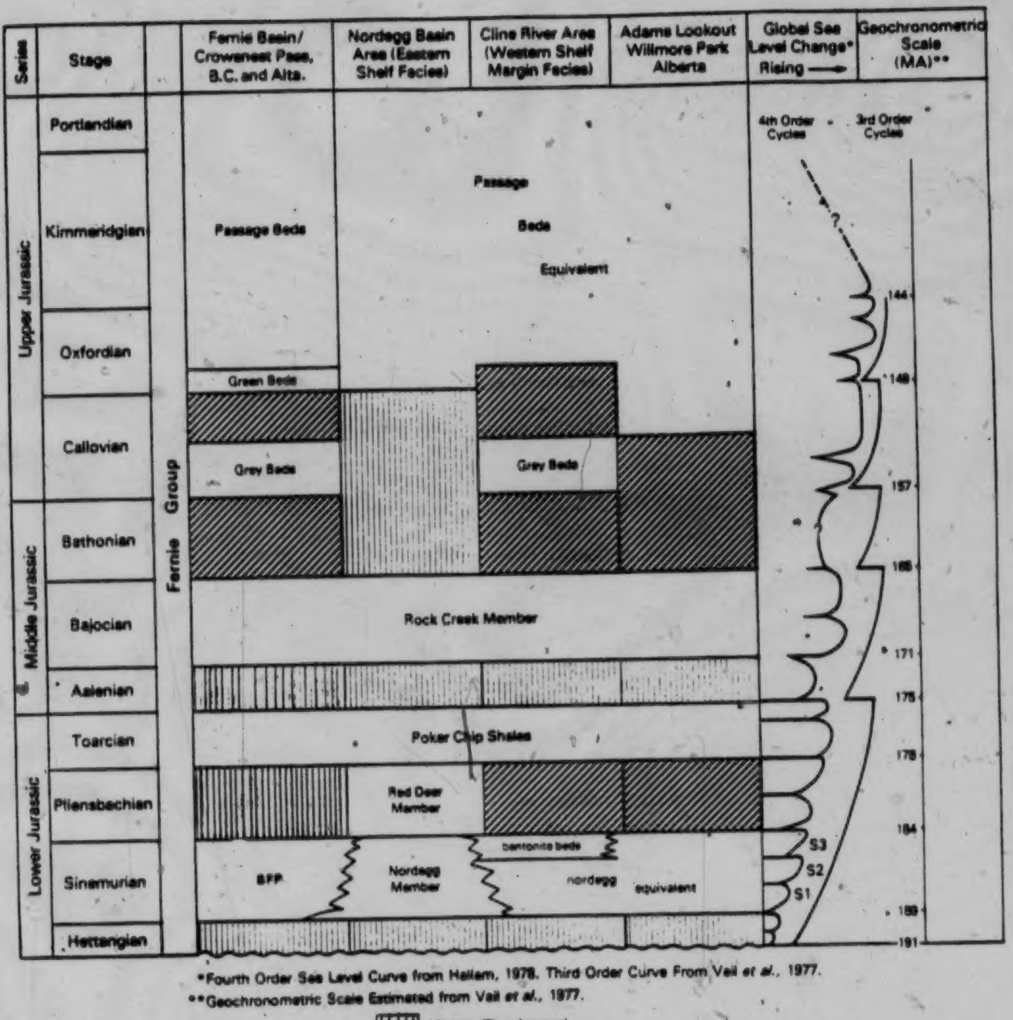
[24] Sections: 60, 83,84, 85, 86, 87, 99, 147, 164, 165, 166, 167, 170, 171, 172, 173, 174, 175, 176, and 320

[25] Sections: 1, 161, 162, 164, 166, 171, 173, 174, and 175

[26] A single sample of a *Lingula* rich sandstone from the SEMP yielded 1.86% P_2O_5 - Section 91

[27] Sections: 147, 164, 165, 166, 172, and 173

[28] Most terminology from Frebold 1957 and Frebold 1969



*Fourth Order Sea Level Curve from Hallam, 1978. Third Order Curve From Vail *et al.*, 1977.

**Geochronometric Scale Estimated from Vail *et al.*, 1977.

Figure 19. Age, nomenclature, sealevel rises, and lithologies — Fernie Group, Alberta and southeastern British Columbia (modified from Frebold, 1957).

Basal Fernie phosphate zone (BFP)

Phosphate is found at the base of the Fernie Group, directly above an unconformable contact with the underlying Triassic, Permo-Pennsylvanian, or Mississippian strata. A generalized isopach map of P_2O_5 values (Fig. 21) normalized to a 2 m thickness shows higher values concentrated in the west and southwest. In most eastern exposures, where Sinemurian age strata are preserved, this contact is represented by a thin (<1 m) phosphatic, pebbly sandstone or conglomerate. Fossil concentrations are also found at some localities. In Western localities in the Fernie Basin, Cascade River Valley (Banff Park), and the North Saskatchewan River region (Areas I, II and III respectfully; Fig. 20) phosphate is pelletal and found within the lower 5 m or so of the contact. These three regions have the best phosphate potential for the entire Fernie Group.

In the Nordegg Basin region (Fig. 20) Sinemurian age strata equivalent ot the BFP are represented by a thick (up to 50 m) succession of sporadically phosphatic (1-3% P_2O_5) chert and cherty limestones, called the Nordegg Member. A thin (<30 cm) phosphatic sandstone containing up to 5% P_2O_5 is found directly above the Nordegg Member (Fig. 22).

Grade / thickness combinations are best within Areas I, II, III (Fig. 20) in the westernmost Front Ranges where pelletal phosphate is found. Classes of deposits vary from Class B (>24% P_2O_5 for a minimum 2 m thickness) in Area I to Class J (6-12% P_2O_5 for a minimum 1 m thickness) in Area III. Area IV, in northern Jasper Park, contains a limited (?) area of J Class deposits.

Within Area I the phosphate potential seems the best in the southernmost outcrops of the BFP and apparently diminishes northward up the Elk Valley toward Kananaskis Park. It should however be noted that the data distribution in the northern Elk Valley is very limited. Pelletal phosphate rock in the southern Fernie Basin area is gradually replaced by low grade phosphatic sandstones in the northern Elk Valley - Kananaskis area and by slightly phosphatic shales north of Kananaskis Park in the Ribbon Creek area (Fig. 22).

In area II, along the Cascade River Valley in Banff National Park, pelletal phosphate rock in the BFP zone varies in grade / thickness from Class K to G

Table 15. Average Phosphorous, Vanadium and Uranium Values - Fernie Group.

MEMBER OR BED	AVERAGE P_2O_5 ANALYSIS (PERCENT)	STANDARD DEVIATION P_2O_5 ANALYSIS (PERCENT)	n	AVERAGE VANADIUM ANALYSIS (PPM)	STANDARD DEVIATION VANADIUM ANALYSIS (PPM)	n	AVERAGE URANIUM ANALYSIS (PPM)	STANDARD DEVIATION URANIUM ANALYSIS (PPM)	n
Passage Beds	0.20	0.09	65	104	31	65	2.8	0.6	65
Oxfordian Beds	0.20	0.09	17	117	52	17	3.0	0.8	17
Grey Beds	0.29	0.10	40	130	80	40	2.7	1.2	40
Rock Creek Mbr.	0.27	0.23	78	124	92	78	3.8	2.2	73
Poker Chip Sh.	0.38	0.22	161	218	231	159	11.8	8.3	153
Red Deer Mbr.	0.71	0.20	9	268	111	9	10.5	3.7	9
Bent.& Cal. Sh.	0.58	0.46	102	429	586	102	17.4	10.8	102
Nordegg Mbr.	0.71	0.57	58	110	205	58	6.2	8.6	58
Nordegg Sh.$	0.67	0.45	19	686	696	19	21.8	16.2	19

*n Number of Samples

$ Non-phosphatic shales below Nordegg Member

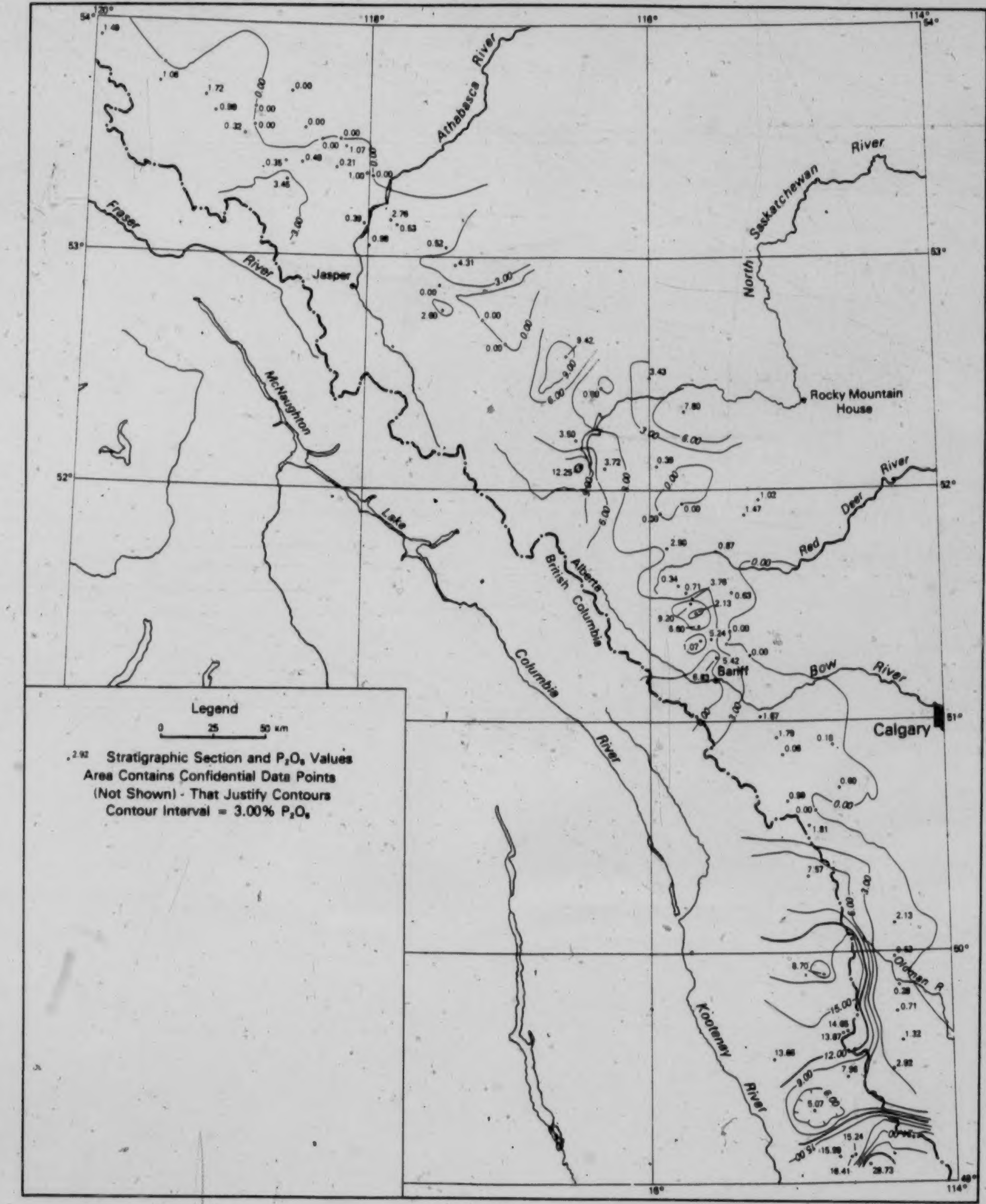

Legend
0 25 50 km
2.92 Stratigraphic Section and P_2O_5 Values
Area Contains Confidential Data Points
(Not Shown) - That Justify Contours
Contour Interval = 3.00% P_2O_5
54°
120°
118°
116°
114°
53°
52°
51°
50°
49°
Athabasca River
Fraser River
Jasper
McNaughton Lake
North Saskatchewan River
Rocky Mountain House
Red Deer River
Alberta
British Columbia
Banff
Bow River
Calgary
Columbia River
Kootenay River
Oldman R.
0.00
3.00
6.00
9.00
12.00
15.00

Figure 21. Isopach map of P_2O_5 values in Lower Fernie Group (BFP horizon) over 2.0 metres thick

(Appendix 5), with no internal trends apparent except that pelletal rock becomes phosphatic sandstone northward, and becomes phosphatic shale southward.

Area III extends from the northwest border of Banff National Park, northward to the North Saskatchewan River. Here, phosphate potential is believed to be consistently in the J Class of deposits (6-12% P_2O_5 for a minimum 1 m thickness). Pelletal phosphate rock is found at the contact and as high as 16 m above the contact (Section 385).

Area III, excluding the portions in Banff Park, has the best potential for future development in Alberta. The only land use restriction in place at the present time is the Eastern Slopes Land Use Management Policy which places Area III in a "Prime Protection Zone" i.e. no mineral development (Fig. 1). Area II is entirely within Banff National Park and Area IV within Jasper National Park. Area I, in the Fernie Basin of British Columbia, has the best geological potential for future development and currently is free of any political constraints. The Fernie Basin area may contain over 2 billion t[29] of subsurface phosphates, as the basin is a large synclinal structure with surface outcrops on the east and west flanks. If this subsurface phosphate could be proved to be continuous throughout the Fernie Basin, this would represent a vast resource potential for possible future insitu recovery programs.

The Fernie Group and the BFP zone within it, occupies a structural / stratigraphic / topographic position that is quite favorable to either open pit or underground mining. The formation is usually found in intermontaine valley areas, at relatively low elevations, with dips somewhat flatter than those found in the mountain range areas, and is overlain by Middle and Upper Jurassic Fernie Group soft shales (Fig. 5, Plate 1A). On the other hand, due to the incompetent nature of the Fernie, local structural folding, faulting, and near surface creep can complicate mining conditions. Structural thickening of the BFP by faulting is known to exist in the vicinity of Section 205 (north of Crowsnest Pass) and possibly in the Lizard Range (near Section 207).

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[29] Based on a crude rectangular shape of 74 x 12 km, assuming a 1 m thickness of BFP horizon over the entire area

Nordegg Member lower shale phosphate (NMLSP)

The cherty limestones and calcareous bedded cherts that form the Nordegg Member are often underlain by an organic-rich black shale zone (Fig 19). These shales are commonly slightly phosphatic (1-4% P_2O_5 range) and are up to 3 m thick; however none have a grade / thickness combination sufficient to place them in at least a J Class standing (Table 16).

This zone does not have any economic potential.

Nordegg Member Phosphate (NMP)

The Nordegg Member is known to contain disseminated phosphate debris, and at one locality (Section 5, Table 17) phosphate nodules (Fig. 19). While thicknesses of the phosphatic zones can exceed 17 m, corresponding grades never exceed 4% P_2O_5 (Table 17). However, the Nordegg Member is not phosphatic throughout in any given section, nor is the member everywhere phosphatic in a regional sense. The NMP has little economic potential.

Fernie Oxytoma Phosphate (FOP)

The top of the Nordegg Member is frequently marked by a fossil hash horizon containing the pelecypod *Oxytoma cygnipes* an index fossil for the Sinemurian (Frebold, 1957). A phosphate pellet-bearing sandstone, or pebbly conglomerate, is often found immediately above or in the place of the *Oxytoma* bed (Fig. 19). Section 23, Nordegg shows the best grade / thickness combination observed for the FOP, reaching a Class J. All other sections are in the M, J or L Class (Table 18).

The FOP is deemed not to have any economic potential.

Red Deer Member Phosphate (RDMP)

Phosphate has been identified in the Red Deer Member primarily in Banff National Park and east of the Park (Fig 19). The Red Deer Member is lithologically very similar to the overlying Poker Chip shales and the underlying Sinemurian age strata. Frebold (1969) has identified the Red Deer Member only from fossil evidence, and only in a limited area. Only one occurrence (Section 385), contains significant amounts of phosphate (8% P_2O_5 over 0.70 m - Class K). The phosphate

Table 16. Lithologic and Chemical Analysis Data - Nordegg Member Lower Shale Phosphate (NMLSP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
13	Sh,intbd	1.20	2.09	830	81.2	2.09	1.25	4	L
23	Sh,intbd	0.20	3.70	1000	59.0	0.74	0.37	3	M
169	Sh,intbd	1.50	2.30	880	37.1	2.30	1.72	1	L
177	Sh,phost	1.30	1.65	286	38.9	1.65	1.07	2	L
183	Sh,phost	3.00	1.84	180	71.9	1.84	1.84	1	L
190	Sh,phost	0.80	1.95	237	56.2	1.56	0.78	5	M
324	Sltst,phost	0.15	1.06	120	9.3	0.16	0.08	1	M

* Number of Samples

Table 17. Lithologic and Chemical Analysis Data - Nordegg Member Phosphate (NMP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
4	Ls;phost	0.50	1.58	60	2.0	0.79	0.39	1	M
5	Ss;nod	4.00	3.90	40	9.5	3.90	3.90	1	L
13	Ls;phost	17.90	1.45	68	3.7	1.45	1.45	7	L
23	Cht;phost	1.60	1.01	100	8.0	1.01	0.81	5	L
26	Ls;phost	6.00	3.14	40	4.0	3.14	3.14	1	L
101	Ls;lntbd	1.30	2.30	200	10.6	2.30	1.49	3	L
324	Ls;phost	3.60	1.13	68	3.9	1.13	1.13	2	L
326	Ls;phost	5.50	0.53	20	0.9	0.53	0.53	3	M

* Number of Samples

occurs as pellets and is tentatively assigned to the Red Deer Member based on stratigraphic position, with no definite fossil evidence being present. All other occurrences are in the L or M Class (Table 19).

Toarcian Poker Chip Shale Phosphate (TPCP)

Some intervals within the Poker Chip shale beds are known to be phosphatic to a slight degree (1-5% P_2O_5). Only one specific zone could be identified in more than one section, i.e. at the top of the member a phosphatic sandstone or phosphate conglomerate is found in places (Sections 9, 190). Section 190 has the best potential for this zone (K Class); however, Section 407 is worthy of note as numerous phosphate zones are found over a 2.74 m interval within the member yielding an average grade of 5.12% (Table 20).[30] All other localities are in the M or L Class (Table 20).

Fernie Rock Creek Member Lower Phosphate (FRCLP)

Phosphate is commonly found near the base of the Rock Creek Member (Fig. 19). The Rock Creek Member consists of shales and sandstones, with the FRCLP being associated with the lowermost sandstone and shales in the member (Fig. 30). Phosphate is expressed as nodules, pellets or unidentified debris generally found in a calcareous sandstone. Phosphatic zones tend to be less than 2 m thick with corresponding grades less than 6% P_2O_5 (Table 21). Taken over a normalized 1 m interval all grades are in the 2-7% range. Sections 220 (Lodgepole Creek, British Columbia) and 417 (Nordegg) are the only occurrences that reach at least a J Class standing (6-12% P_2O_5 for a minimum 1 m interval). Sections of FRCLP a few kilometres south of Nordegg are also known to be in the J to H Classes (J.M. Hamilton, Cominco Ltd. pers. comm.), but are reported to contain large amounts of pyrite.

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[30] It is however, not certain that these phosphate horizons are within the Poker Chip Shales. Based on known stratigraphic thicknesses they would however appear to be.

Table 18. Lithologic and Chemical Analysis Data - Fernie Oxytoma Phosphate (FOP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
23	Phos:phost	0.27	25.44			6.87	3.43	2	J
123	Ls:phost	0.20	4.00	65	105.5	0.80	0.40	2	M
137	Ss:pell	5.20	3.10	91	11.3	3.10	3.10	2	L
324	Ss:pell	0.30	6.80	20	8.6	2.04	1.02	1	K
367	Ls:phost	1.00	2.00	160	6.9	2.00	1.00	1	M

* Number of Samples

Table 19. Lithologic and Chemical Analysis Data - Red Deer Member Phosphate (RDMP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5% (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
327	Ls,phost	0.20	4.10	100	36.9	0.82	0.41	6	M
335	Ls,phost	6.00	1.30	110	5.3	1.30	1.30	2	L
375	Ls	2.00	1.00	510	7.9	1.00	1.00	1	L
385	Phos,pell	0.70	8.00	80	37.1	5.60	2.80	1	K

* Number of Samples

Table 20 . Lithologic and Chemical Analysis Data - Toarcian 'Poker Chip Shale Phosphate (TPCP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
9	Sh;pell	0.30	4.50	400	63.6	1.35	0.67	1	M
111	Sh;phost	2.98	1.20	150	14.8	1.20	1.20	1	L
190	Sh;phost	0.10	22.30	800	30.3	2.23	1.12	1	K
405	Sh	0.25	2.20	200	24.4	0.55	0.27	1	M
406	Sh	0.25	1.20	200	16.8	0.30	0.15	1	M
407	Sh	2.74	5.12	436	105.2	5.12	5.12	11	L
254	Ls;phost	5.00	1.87	290	28.2	1.87	1.87	1	L
351	Ls;phost	1.50	1.00	190	12.7	1.00	0.75	1	L
367	Sh;phost	4.50	1.40	170	8.9	1.40	1.40	1	L

* Number of Samples

Table 21. Lithologic and Chemical Analysis Data - Fernie Rock Creek Member Lower Phosphate (FRCLP)

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5%	 VANADIUM (ppm)	 URANIUM (ppm)	P_2O_5% (1 m.)	P_2O_5% (2 m.)	N*	CLASS
42	Sh;phost	6.00	2.90	260	15.7	2.90	2.90	1	L
181	Ss;nod		12.20†					1	
193	Ss;nod	0.20	0.20	90	2.0	0.04	0.02	1	M
205	Ss;phost	1.00	2.70	60	4.2	2.70	1.35	1	M
208	Ss;phost	1.91	5.36			5.36	5.12	3	L
220	Ls;pell	1.00	6.10	110	13.9	6.10	3.05	1	J
245	Sh;phost	4.40	1.10	120	6.2	1.10	1.10	1	L
262	Sltst;pell	1.52						1	
275	Ss;nod	0.45						1	
283	Ss	1.10	2.03	31	6.0	2.03	1.12	2	L
286	Ss;pell	1.40	1.56	58	4.4	1.56	1.09	3	L
335	Ss;phost	1.70	2.20	240	6.8	2.20	1.87	1	L
351	Ss;pell	2.00	2.70	110	5.7	2.70	2.70	1	L
367	Sh;phost	1.90	2.20	110	6.4	2.20	2.09	4	L

* Number of Samples

† Assay of Nodules Only

Table 22. Lithologic and Chemical Analysis Data - Fernie Rock Creek Upper Phosphate (FRCUP).

SECTION	LITHOLOGY	THICKNESS (m)	P_2O_5%	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5% (1 m.)	P_2O_5% (2 m.)	N*	CLASS
9	Ss;nod	4.00	0.17	50	2.2	0.17	0.17	1	N
13	Ss;nod	1.00	2.02	60	2.6	2.02	1.01	1	M
26	Ss;nod	0.20	0.70	80	2.5	0.14	0.07	1	N
181	Ss;phost	3.00	1.20	160	1.9	1.20	1.20	1	M
196	Ss;phost	0.40	4.30			1.72	0.86	1	M
256	Ss;nod,cmt	0.30	0.20			0.06	0.03	1	N
346	Ss;pell	2.00	0.08	20	5.2	0.08	0.08	1	N

* Number of Samples

Table 23. Resource Estimates for the Basal Fernie Phosphate (BFP).
Alberta and British Columbia

AREA	LAND[+] STATUS	CLASS[$] AVERAGE	OUTCROP LENGTH (km)	GROSS TONNES? (300 m.)	GROSS TONNES? (50 m.)	n*
IV-Fig.20	JNP-ALTA	J	40	32.0	5.3	1
III-Fig.20	PPZ-ALTA	J	120	96.0	15.9	4
III-Fig.20	BNP-NORTH	J	34	27.0	4.5	1
II-Fig.20	BNP-SOUTH	J-H	114	91.0	15.1	8
I-Fig.20	DP-ALTA	J	10	8.0	1.3	1
I-Fig.20	FB-B.C.	J-H	74	59.0	9.8	3
I-Fig.20	FB-B.C.	B(2m)	9	14.4	2.4	1
I-Fig.20	FB-B.C.	F (2m)	201	323.0	53.7	7
I-Fig.20#	FB-B.C.	E (1m)	(201)	(161.1)	(26.8)	7
TOTALS			602	650.4 (488.4)	108.0 (81.1)	27

+ Land Status Symbols; JNP-Jasper National Park, BNP-Banff National Park, PPZ - Prime Protection Zone,
DP- Developement Permitted (some restrictions), FB - Fernie Basin

$ Class; for Class description see Fig. 6. All Clases Based on 1.0 metre thickness unless otherwise noted.

? Tonnes; All figures in Millions of Metric Tonnes.

* n; Number of Stratigraphic Sections used in calculations.

Same area as previous line, based on area being Class E (18-24% P2O5 over at least 1m)

Fernie Rock Creek Upper Phosphate (FRCUP)

Phosphate, as nodules and less commonly pellets, is found at the uppermost sandstone in the Rock Creek Member (Fig. 19). Nodules usually comprise less than 20%, by volume, within a given bed. Seven occurrances of the FRCUP zone are known in a region extending from the Jasper area (Section 181) south to the Crowsnest Pass (Section 196). All are in the easternmost Front Ranges or Foothills belt.

None of the occurrances found is of any economic significance, as all are the N, M or L Class (Table 22).

Summary of Resource Potential - Fernie Group

The Basal Fernie phosphate zone is the only zone with economic potential for the foreseeable future. A crude estimate of the amount of in situ phosphate rock present in the BFP is presented on Table 23. The methodology and assumptions outlined in Appendix 6 were applied in calculating these estimates. It must again be stressed that these numbers are only approximations and do not attempt to say how much phosphate rock could be economically produced.[31] These estimates are best used in comparing one potential development area to another.

It is apparent from Table 23 that the Fernie Basin area, British Columbia has the largest resource potential, in terms of grades, thicknesses and potential tonneages. In Alberta 59% of the available resource lies within the two national parks, 38% within the "Eastern Slopes Prime Protection Zone" (no mineral development); only 3% lies within a potentially exploitable area. This potentially exploitable area lies in the Crowsnest Pass (Fig. 20) where no actual data on the BFP is available for the Alberta side. Calculations are based on data from British Columbia about 2 km north of the Alberta border at the abandoned Crow Phosphate mine. Many of the resource block areas shown in Table 23 are very low grade ores. In terms of 18% P_2O_5/ 1 metre grade material or better, there is an estimated 29 to 175 million t present in the Fernie Basin area. This of course depends on whether the most or least optimistic figure is used for downdip projection of the phosphate beds. It should be borne in mind while examining these figures that the 1981 consumption of imported phosphate rock in Canada was 3.6 million t of high grade rock.

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[31] At the present time no phosphate rock in Canada is economically produced

Miscellaneous Occurrences

A number of other phosphate showings are present in Alberta; however, very little is known about them. These miscellaneous occurrences are discussed below:

Athabasca Group - Precambrian Helikian

Thin (<10 cm) phosphorites have been reported from the Precambrian Upper Wolverine Point Formation, Athabasca Group by J. Wilson (pers. comm.).[32] The phosphate is found within a series of tufaceous sediments and is expressed as a gray to colorless, zoned fluorapatite with low birefringence. No bulk chemical analysis is available; however, microprobe analysis on the phosphate cement revealed 40.55% P_2O_5, 4.3% F, 1% Na^+, Mg^+, Al, 0.3% V, Mn and Fe, based on two sample points only.

Christie (1981) has reported oolitic, cement, and fracture-fill type phosphates also from the Wolverine Point Formation of the Athabasca Basin. Grades of up to 30% P_2O_5 within intraformational conglomerates have been discovered by Eldorado Nuclear Ltd. (Christie, 1981), however most zones seem to be less than 0.5 m thick (up to 1 m is however present) with corresponding grades around 10% P_2O_5.

Flume Formation - Upper Devonian

A 30 cm thick, pelletal phosphate zone has been reported from the Flume Formation at Kakwa Lake, British (Columbia B. Chatterton pers. comm.) [33] Kakwa Lake is approximately 8 kms west of the Alberta border, northwest of Willmore Wilderness Provincial Park (Latitude 54°, Longitude 120°10'). This same zone may be present in the Western Main Ranges of Willmore Park.

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[32] J. Wilson is undertaking sedimentological/stratigraphic analysis of the Athabasca Group in Alberta for the Alberta Geological Survey. All of the data for this study is supplied by uranium exploration drillcores - much of which is confidential at the present time.

[33] University of Alberta, Geology Department, Professor of Paleontology.

Nordegg Formation Subsurface - Lower Jurassic

In 1976, J.R. Century Petroleum Consultants Ltd. acquired Quartz Mineral permits in the vicinity of Tp. 59, Rge 11, W5M with the intent of evaluating the phosphate potential of the Nordegg Formation in the subsurface (Fig. 2). Their purpose was to evaluate the Nordegg with respect to in situ solution mining potential. Low phosphate values, derived from core, (1-4% P_2O_5) coupled with the 1500 m depth to the Nordegg, caused the project to be dropped. The P_2O_5 values encountered within the subsurface are in a very similar range to those encountered in outcrops of the Nordegg Member in this study (Table 17).

Shaftesbury Formation - Upper / Lower Cretaceous

Phosphate, in the form of densely packed fish scales, is reported to occur within the well known stratigraphic marker horizon known as the "Fish Scale" horizon on the east side of the Birch Mountains in northeastern Alberta (R. Green, pers. comm.). [34] (Fig. 2). The bed is 30 cm thick and lies within a thick sequence of shales, with the Fish Scales marking the Upper / Lower Cretaceous boundary. No grades are available. The Fish Scale horizon is known to be very widespread throughout most of Alberta.

Dunvegan / Shaftesbury Formation

Phosphatic, uraniferous black shales are reported to be present near the Shaftesbury - Dunvegan Formation contact in the Birch Mountains of northeastern Alberta (J. Stewart, First Nuclear Corporation, pers.comm.). Surface samples collected by First Nuclear revealed up to 3.94% P_2O_5, 0.027% U_3O_8, 0.2% vanadium and up to 11.90% carbon. The bed thickness is unknown; however, gamma-ray log expression suggests several tens of metres. This zone outcrops along the eastern edge of the Birch Mountains and extends into the subsurface to the west where it is overlain by younger Cretaceous strata and glacial deposits to an average thickness of 76 m.

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[34] R. Green is a Vice-President of the Alberta Research Council.

Smoky Group - Upper Cretaceous

The Clear Hills iron ore deposit in northwestern Alberta is reported to contain 1-2% P_2O_5 as finely disseminated phosphate grains within an opaline cement (Fig. 2) (Petruk et al., 1976). This cement binds the goethite-bearing ooliths, which compose the main ore. Apatite is also known to be incorporated into some of the concentric rings of the ooliths. The Clear Hills iron ore deposit varies from 1.5 - 9.1 m thick, grades 32-36% Fe, with total reserves, proven, probable and possible of 1.1 billion tons (Bertram and Mellon, 1973). If this iron ore deposit is ever mined, phosphate might be produced as a co-product.

Other Investigations

A number of other geological formations were examined in a cursory manner to explore for any phosphate potential. None of these results show any phosphate potential but are however summarized in Table 24. While Table 24 is not intended to be exhaustive in describing phosphate content in other formations in the Western Canadian Sedimentary Basin, it does provide a glimpse of what potential may be present. Most of the Upper Cretaceous to Tertiary clastic units have P_2O_5 values all very close to 0.22%. Slightly higher values are apparent in the Belcourt and Paskapoo Formations. The carbonates in the Palliser Formation are strongly deficient in phosphorous.

B. Uranium, Vanadium, Fluorine and R.E.E. in Phosphates

Uranium in Phosphates

The uranium content in phosphatic rocks examined in this study is found to have a mean value of 34.3 ppm [35], based on all samples with P_2O_5 contents of 1% or greater. Figure 23 shows a graph of the mean uranium values for various groups of increasingly phosphatic rocks, the value rising with increasing overall P_2O_5 content and decreasing P_2O_5 class size and In Figure 23 those groups over 18% P_2O_5 show a range of uranium values in the 67-107 ppm. By comparison DeVoto and Stevens (1980) estimate the average uranium content in the "Free World" phosphorites to be in a similar range of 60-130 ppm

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[35] n=444, std. dev. = 41.1, min. = 0.5, max. = 295.1

Table 24. Phosphate Content in Selected Geological Formations.

FORMATION	AGE	LOCATION	LITHOLOGY	THICKNESS (m)	P_2O_5%	OTHER ASSAYS
Paskapoo	Tertiary (Lacustrine)	10-10-25-42W4 Alberta	Shale	1.5 (24 m. below surface)	*0.50	
Luscar (Moosebar Mbr.)	Lower Cretaceous	Grande Cache Open Pit Mine	Glauconitic Sand Horizon	1.0 (approx.)	*0.21	Vanadium 140 ppm
Clearwater	Lower Cretaceous	Ft. McMurray	Glauconitic Sand Horizon	?	*0.20	Vanadium 120 ppm
Wapiabi	Upper Cretaceous	50°47', 114°52'	Black Shales	20	*0.22	
Blackstone	Upper Cretaceous	50°39' 114°35'	Shale, minor sst interbedded	366	0.20 (n=10)	V = 152 U = 3.6
Nikanassin	Upper Jurassic Lower Cretaceous	?	Sandstone/Shale Interbedded	?	*0.24	
Kootenay	Upper Jurassic Lower Cretaceous		Sandstone/Shale Interbedded		*0.24	
Belcourt	?	?		variable	0.87 (n=5)	
Banff	Mississippian	Crowsnest Pass	?	variable	0.26 (n=28)	
Palliser	Upper Devonian	Cadomin Quarry	Limestone	250	0.005 (n-19)	

*Based on single sample only

range. Scatter diagrams of uranium values versus phosphate values (>1% P_2O_5)[36] shows a broad scatter of points in a crudely positive linear trend. The correlation coefficent (R), based on $\log_{10}$ transformed data, indicates that roughly 28% (R^2) of the variability in uranium content is accounted for by the linear phosphorous-uranium relationship. [37] Several different grade groups of phosphatic rocks were formed to see if this correlation could be improved (Fig. 23). The R value is highest (0.53) in the group containing 0-32% P_2O_5 and drops to no linear relationship (at 95% confidence) for the 6-12%, 12-18%, and 24-32% P_2O_5 groups. Similarily, R values of 0.21-0.22 are present in the 12-32% and 18-32% P_2O_5 groups.

It is therefore apparent that the phosphorous uranium relationship is strongest in the entire sample population regardless of P_2O_5 content and in the 18-32% range. A somewhat weaker correlation (r = 0.35) is present in the 1-6% P_2O_5 group. The foregoing analysis suggests that roughly 72% of the variability in uranium content in the 1-32% P_2O_5 suite of samples is being controlled by some factor(s) other than P_2O_5 content.

The phosphorous uranium relationship was further explored with respect to stratigraphic position or zone. Table 25 shows that this relationship is most strongly developed in the Johnston Canyon Formation in which over 70% of the variability in uranium content is accounted for by the linear positive phosphorous-uranium relationship (R = .83). It appears therefore that positive linear correlations between uranium and phosphorous vary with particular P_2O_5 ranges and with geologic time. Gaushin et al. (1974) considered that a strong positive correlation of phosphorous-uranium on a global scale was not possible, although a particular region may show strong tendencies.

Data on uranium values found within specific phosphatic can be found in Tables 4 to 22 inclusively. Mean values for the formations studied show the Exshaw and Fernie to have the highest values (Table 26). Figure 24 shows an isopach map of uranium content in the Exshaw Formation. Figure 24 suggests an increasing uranium content in an east to west direction, within the Exshaw Formation. All of the means show high standard deviations suggesting a wide scatter of values.[38]

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[36] Taken to the $\log_{10}$ to normalize the otherwise positively skewed data

[37] All of the following correlation coefficients in this section are based on $\log_{10}$ transformed data. This transformation results in near normal distributions for P_2O_5, U and V.

[38] It is of some interest to note that Campbell (1980) reports a mean uranium value for the Exshaw (based on subsurface cores) of 10 ppm (std. dev. = 2,

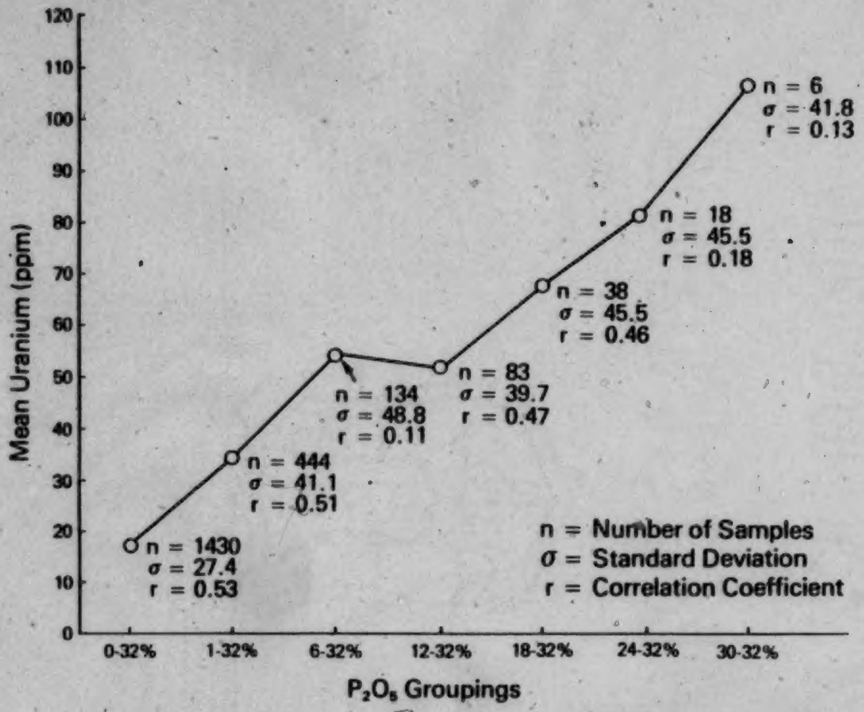

Figure 23. Mean uranium content and correlation coefficients in various classes of phosphatic rocks

Table 25. Correlation Coefficients of the Relationship Uranium-Phosphorous by Formation or Zone, within the Alberta Phosphates.

HORIZON OR FORMATION[1]	CORRELATION COEFFICIENT[2] (r)	SAMPLE NUMBER (n)
Fernie Group	.5261	229
BFPH	.4260	64
Whitehorse Formation	.1413[4]	3
Sulphur Mountain Formation	.3116[4]	13
Mowitch Formation	.7931	23
Ranger Canyon Formation	.7800	62
RCBP	.7364	39
Johnston Canyon Formation	.8372	26
Kananaskis Formation	.7771	17
Tunnel Mountain Formation	.4821[4]	9
All Premo-Pennsylvanian[3]	.7083	97
Exshaw Formation	.1913[4]	34
Exshaw-Whole[5]	.5102	256

[1] All formations or horizons based only on those samples with >1% P_2O_5, unless otherwise noted

[2] All correlation coefficients are at .05 (95%) confidence level

[3] All Permo-Pennsylvanian phosphatic horizons taken together

[4] Null hypothesis Ho=0 accepted at .05 confidence level i.e. no linear correlation

[5] All samples regardless of P_2O_5 contents

Table 26. Mean Uranium, Vanadium and Fluorine Values in Phospahte Rocks of Alberta - via Geological Formations.

AGE	FORMATION GROUP	MEAN U[1]	N	STD. DEV.	MEAN V[2]	N	STD. DEV.	MEAN F[3]	N	STD. DEV.
Jurassic	Fernie	42.6	242	46.8	255	239	433	4.0036	16	.6214
Triassic	Whitehorse	7.7	3	0.6	60	3	69	-	-	-
	Sulphur Mtn.	16.7	13	9.9	148	13	209	4.1321	7	.2425
	Mowitch	14.9	23	11.4	87	23	48			
Permian	Ranger Canyon	19.9	64	21.3	78	67	45	4.2611	19	.2491
	Johnston Canyon	24.3	26	24.0	67	26	53			
Penn.	Kananaskis	14.9	17	16.2	46	17	29	-	-	-
	Tunnel Mtn.	6.0	9	2.9	46	8	23	-	-	-
Dev./Miss.	Exshaw	57.8	34	49.9	446	34	698	3.0888	6	1.1338
PE	Athabasca Group	-	-	-	-	-	-	4.3145	2	0.0502

[1] All values in ppm for rocks with 1% P_2O_5. Neutron Activation method

[2] Values in ppm for rocks with 1% P_2O_5. Wet chemical method

[3] Values in percent (%) based on spot analysis of selected phosphate minerals. Microprobe method

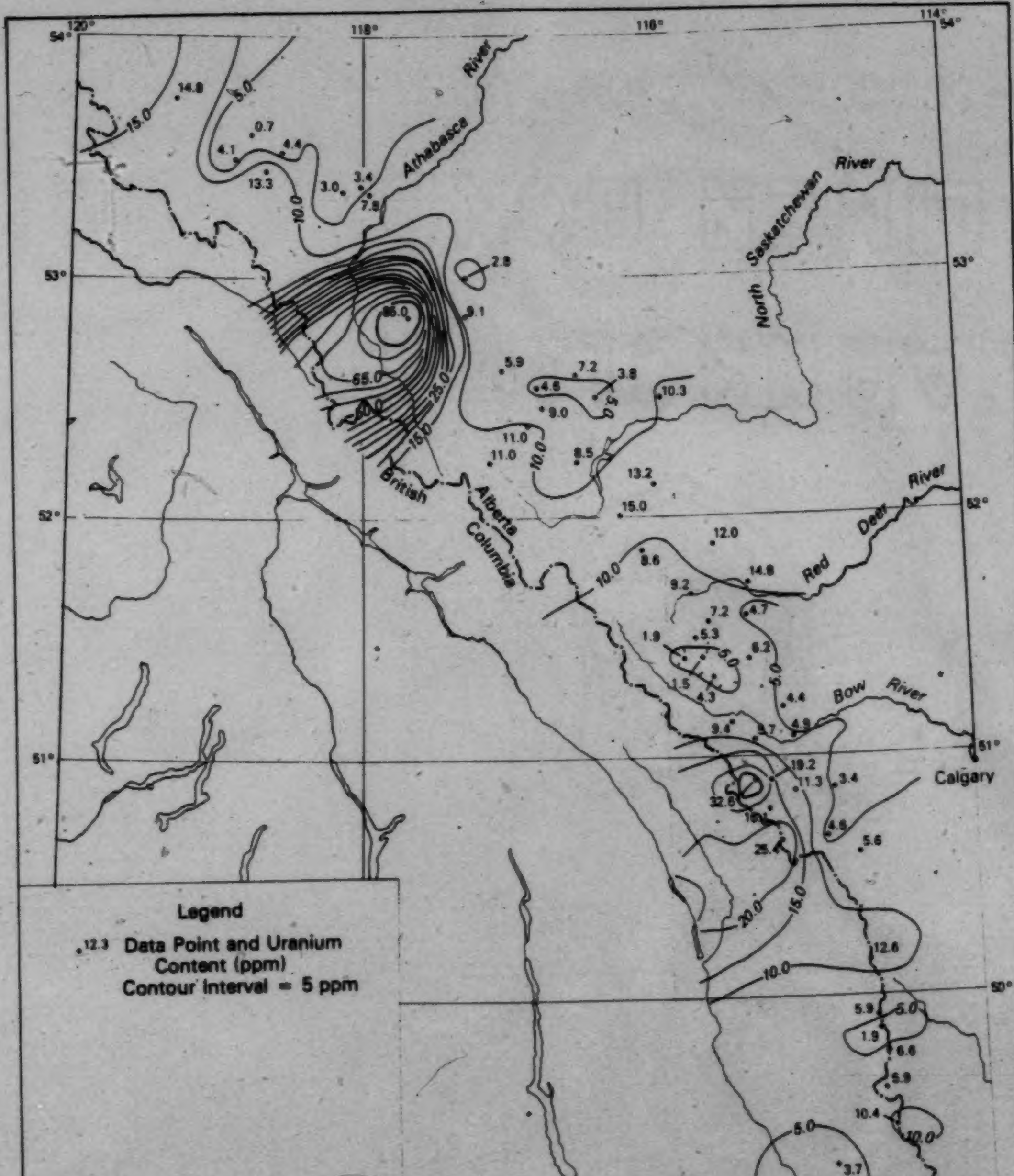
120°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Athabasca River
North Saskatchewan River
Red Deer River
Bow River
British Columbia
Alberta
Calgary
15.0
5.0
10.0
65.0
60.0
25.0
15.0
10.0
5.0
5.0
10.0
5.0
20.0
15.0
10.0
5.0
10.0
5.0
14.8
0.7
4.1
4.4
13.3
3.0
3.4
7.8
2.8
85.0
9.1
5.9
7.2
3.8
4.6
9.0
10.3
11.0
11.0
8.5
13.2
15.0
12.0
8.6
9.2
14.8
7.2
4.7
1.9
5.3
6.2
1.5
4.3
4.4
9.4
9.7
4.9
19.2
11.3
3.4
32.6
10.1
4.8
5.6
25.4
12.6
5.9
1.9
6.6
5.9
10.4
3.7
Legend
12.3 Data Point and Uranium Content (ppm)
Contour Interval = 5 ppm
0
25
50 km

Figure 24. Isopach map of uranium content (ppm) in the Exshaw Formation (weighted averages)

Explaining the presence of anomalously high (relative to crustal averages) quantities of uranium in association with phosphate has been a long standing problem. While this, and most other studies, have been able to show some degree of linear relationship between uranium and carbonate fluorapatite (via P_2O_5 content), most commonly some of the variability in uranium content can not be accounted for by its association with P_2O_5.[39] Starinsky et al. (1982) suggested that uranium content in phosphates increased with increasing diagenesis.

Uranium shows a positive linear correlation with vanadium, particularly in the low P_2O_5 class ranges, reaching a maximum of R = 0.70 for 1-6% P_2O_5 samples. This relationship becomes less strong in the high P_2O_5 class ranges (e.g., R = 0.47 for 18-24% P_2O_5). All of the samples taken as a whole yield r values of 0.49, and for phosphatic rocks (>1% P_2O_5) R = 0.58. It can be concluded therefore, that some of the uranium in phosphates within this study seems related to vanadium, though the chemical or mineralogical association is unknown.

The form that uranium takes in phosphorites has been debated at length. However, the present general consensus seems to be that the uranyl ion (UO_2^{+2}) can be adsorbed onto carbonate fluorapatite crystals, or the tetravalent form U^{+4} can substitute for Ca^{+2} in the crystal lattice (Sheldon, 1959, Starinsky, 1982). Autoradiography, S.E.M. x-ray mapping, x-ray diffraction, and fission track methods all failed to locate discrete uranium-bearing mineralogies within this group of phosphorites. This suggests that the uranium in the phosphorites of this study is adsorbed onto or incorporated into the apatite, as found with most other phosphorites. Gaushin et al. (1974) suggested a maximum of 1-2 atoms of uranium/1000 units cells of carbonate fluorapatite. Values exceeding this range were attributed to the redeposition of phosphate into sea water. Nearly all the samples examined in the present study fall into this "normal" range of atoms/1000 unit cells as described by Gaushin et al. (1974).

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[38](cont'd) n = 155). The present study found a mean value of 14.4 ppm (std. dev. = 17.7, n = 224) for those non-phosphatic Exshaw samples. These results suggest that very little uranium leaching or enrichment of surface outcrops has occured.

[39] Mott and Drever (1983) found correlation coefficents of 0.29-0.45 for P_2O_5 versus U in the Green River Formation, Wyoming. Thompson (1953) in studing the Phosphoria Formation found r values of 0.12-0.92 for the phosphorous/uranium relationship.

The origin of uranium in phosphorites has long been thought be due to dissolved uranium in sea water. More recently, Starinsky et al. (1982) has shown that uranium is derived from organic matter breakdown associated with early diagenetic interstitial mud-formed phosphates. Many of the phosphates in the present study are deemed to be organic rich, based on color and petrographic appearance. Much of the uranium in the phosphorites may be associated with organic matter, as several authors have suggested (Gindy, 1978).

Vanadium in Phosphates

Vanadium is found to have a slight negative linear correlation with P_2O_5 when all phosphatic rocks >1% P_2O_5 are considered (r = -0.03, n = 428).[40] This correlation coefficent is not significant at 0.01 or 0.05 confidence levels, i.e. there is likely no negative linear relationship between these two elements. A slightly stronger negative linear correlation (r = -0.10, significant at 0.01 and 0.05 confidence levels) is present in all samples regardless of P_2O_5 content, i.e. 0-32% P_2O_5. No further groupings of P_2O_5 grades, as was done for uranium in the previous section, could produce any positive or negative linear correlations that were significant to at least 0.05 confidence levels. Scatter diagrams do not indicate any other type of non-linear relationship.

The Phosphorous / Vanadium relationship when considered by formation, yields some linear correlations (Table 27). The Fernie Group seems to have a low negative linear correlation, whereas the Mowitch and Ranger Canyon Formations seem to have a mildly positive linear correlation.

Mean vanadium values in the Phosphoria Formation of the western United States are reported by Gulbrandsen (1967) to be 300 ppm vanadium. Mean values for the formations in the present study range from 46 to 446 ppm (Table 26). Gulbrandsen also states that the vanadium is associated with the organic matter in the phosphates and not the apatite. Love (1967) reports vanadium values up to 2% V_2O_5 in organic-rich, non-phosphatic (?) zones within the Phosphoria. Organic matter was not analyzed in the present study; however, those parts of the Exshaw and Fernie Formations that are organic-rich and not phosphatic (i.e. <1% P_2O_5) have mean V values of 607 and 227 ppm

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[40] All of the following analysis were performed on data transformed to $\log_{10}$.

Table 27. Correlation Coefficients of P_2O_5 versus Vanadium, by Formation, in Alberta Phosphates.

FORMATION/GROUP	CORRELATION COEFFIEIENT	N	SIGNIFICANT @ 0.01 LEVEL?
Fernie	-.1779	226	yes
Sulfur Mountain	-.1729	13	no
Howitch	+.7002	23	yes
Ranger Canyon	+.5707	65	yes
Johnston Canyon	+.2539	26	no
Kananaskis	+.3173	17	no
Tunnel Mountain	+.5273	8	no
Exshaw	-.1908	34	no

with maximum values of 4000 and 2800 ppm respectively. Clearly vanadium is present in significant amounts, and is more likely related to organic matter than to phosphorous concentration. This appears to be the case for most phosphatic rocks, based on the foregoing statistical treatment.

Vanadium contents for individual phosphatic zones are in Tables 4 to 22.

Fluorine in Phosphate

Not all phosphorites collected during the course of this study were systematically "whole rock" analyzed. Fluorine was analyzed, however, in twenty-one representative samples at fifty-three analysis points, on phosphate rocks using the electron microprobe.[41] The mean fluorine value for all phosphate samples analyzed is 4.0855% (Std. Dev. = .5124, n = 53). Figures 25 and 26 show the distribution of fluorine values via petrographic lithotypes and also by geologic age. Fluorine content, with respect to lithotypes, shows a fairly tight clustering and high mean values in the carbonate fluorapatite cements, bones and fluorapatite cement groups; broader ranges and lower mean values for the pellet, microsphorite, and intraclast groups. With respect to age, fluorine is most variable in the Devonian-Mississippian, and Lower Jurassic, least variable in the Precambrian, Permian, Triassic, and Middle Jurassic. The Permian phosphorites are composed mainly of carbonate fluorapatite cement and show the least scatter of fluorine. Conversely, the Jurassic and Devonian-Mississippian consist largely of the pellet lithotypes and both show the largest variation and lowest mean values in fluorine contents. F/P_2O_5 ratios are very consistent at a mean value of 0.12 for all data (Table 28). F/P_2O_5 and CaO/P_2O_5 ratios are slightly lower in the Exshaw Formation and the Athabasca Group.

Fluorine in the Phosphoria Formation phosphorites is reported to be in the range of 2.20-4.40% (Gulbrandsen, 1967). The presence of fluorine is generally attributed to its being incorporated into the fluorapatite crystal lattice. However, in the present study, some fluorine is present as fluorite in some of the Permian phosphorites.

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[41] See "Laboratory Procedure" section for operating conditions

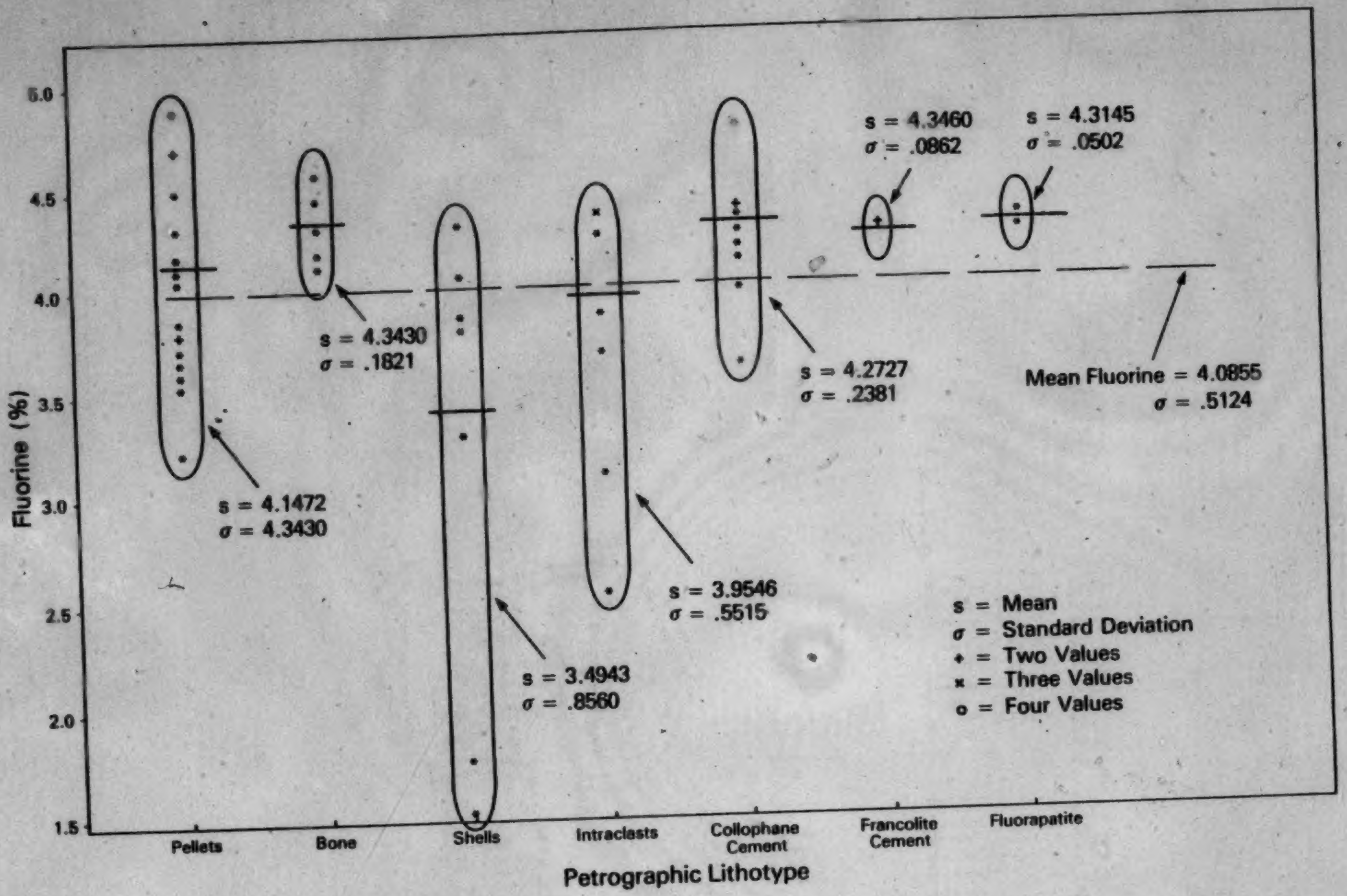

Figure 25. Fluorine content in petrographic lithotypes in phosphorites

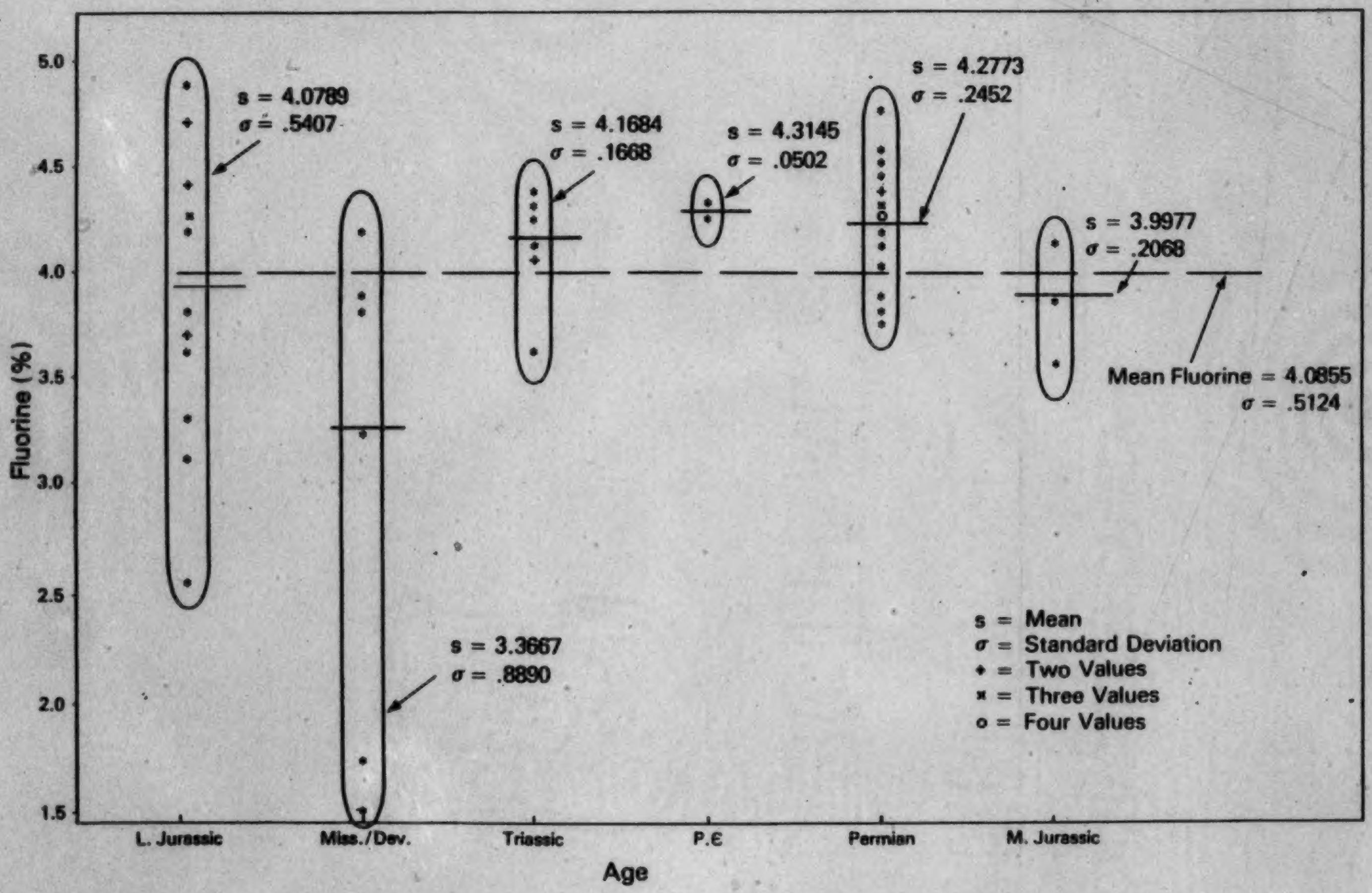

Figure 28. Fluorine content in phosphorites by geological age

Rare Earth Elements in Phosphates

The rare earth element (R.E.E.) content of phosphorites in this study was briefly examined by forming four composite samples for analysis by Neutron Activation - Gamma Spectrometry. These four samples are believed to represent R.E.E. compositions in phosphorites from the Devonian-Mississippian, Permo-Pennsylvanian, Triassic and Jurassic periods.

The average R.E.E. contents of the samples analyzed are all the above "average" values for worldwide phosphorites (Table 29). In particular, the Fernie Group shows values for the elements Dy, Ho, Tm and Yb that are twice as high as the "average". No depletions with respect to average REE contents are seen in any of the phosphorites of this study.

Altschuler et al. (1967) outlined the R.E.E. content and its potential for development in both the Phosphoria Formation of the western United Sates and Florida deposits. These authors suggested that based on present (i.e. 1967) production rates of phosphoric acid in the U.S.A., approximately 6000-7000 tons of R.E.E. could be recovered annually from phosphates. They further outlined the resources of R.E.E., based on then current phosphate reserves, to be approximtely 2.0 million tons for the U.S.A. Subsequently, Altschuler (1980) determined the "average" R.E.E. composition for worldwide marine phosphorites, and in general, found enrichments [42] above the "average shale" to occur for the following elements: La, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y. None of the remaining R.E.E. described by Altschuler, i.e. Ce and Pr, showed depletion relative to "average" values. Altschuler et al. (1967) did, however, describe a Cerium depletion in several worldwide phosphate occurrences.

Trace Elements in Phosphates

The trace element composition of phosphorites of this study (Table 30) compared to "average" values (Altchuler, 1980, shows a wide variation in composition. Altchuler described enrichments in Ag, Ca, Mo, Pb, Se, Sr, U, Y, and Zn, and depletions in B, Co, Ga, Hg, Li, Sn, Ti and Zr within worldwide phosphorites, with other trace elements being in normal abundance. The present study (Table 30) shows enrichments in Ag, As, Cd, Mo, Ni, Se, U, Zn, Zr and depletions in Mn and Ti, with most other elements analyzed in near

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[42] Enrichment was defined by the author to be 2x "normal" abundance.

Table 28. Principal Chemical Characteristics of Apatites in Phosphates of Alberta and British Columbia, Compared to Other Apatites.

RELATIONSHIP	F/P_2O_5	CaO/P_2O_5	CaO	P_2O_5	CO_2	F	Na_2O	MgO
Alberta/B.C.								
Lower Jurassic	.12	1.43	48.034	33.532	1.96	4.709	0.333	0.698
Middle Jurassic	.11	1.39	50.292	36.181	3.00	3.998	0.224	1.070
Triassic	.11	1.39	51.319	36.947	2.19	4.168	0.959	0.658
Permian	.12	1.40	51.615	36.764	1.13	4.277	0.540	0.558
Devonian/Mississippian	.10	1.32	44.644	33.734	0.99	3.367	0.517	0.815
PE	.11	1.35	54.883	40.565	?	4.315	0.74	0.649
Lithotypes								
Pellets	.12	1.41	49.987	35.574		4.147	0.439	0.731
Bones	.12	1.41	51.885	36.842		4.434	0.886	0.474
Shells	.11	1.37	44.675	32.619		3.494	0.580	0.838
Intraclasts	.12	1.45	48.386	33.484		3.955	0.397	0.649
Primary Cement	.11	1.38	52.653	37.477		3.955	0.482	0.575
Francolite Cement	.12	1.37	51.677	37.713		4.273	0.825	0.629
Fluorapatite Cement	.11	1.35	54.883	40.565		4.346	0.074	0.649
All Samples (Lithotypes) n=53	.12	1.39	50.449	36.324	1.66	4.085	0.516	0.649
Others								
Phosphoria Fm.			53.4–55.3	36.5–40.5	0.8–3.5	3.8–4.2	0.2–1.2	
Arch (1980)								
Diagenetic Rock	0.13	2.26						
Authigenic Rock	0.10	1.40						
Authigenic Pellets	0.10	1.42						
Bremner (1978)								
Authigenic	0.11	1.67						
Durango Fluorapatite[1]	0.087	1.32						
Theoretical Fluorapatite[4]	0.089	1.32	55.6	42.2	0.0	3.77	0.0	0.0
Theoretical Francolite	0.148	1.62	55.1	34.0	6.3	5.04	1.4	0.7
Side Daoul[2]	0.12	1.29						
Hydroxyapatite	0.0				0.0	0.0		
West Senegal[3]	0.11	1.33						
Dahllite	?	?			1.0	1.0		

[1] Lucas, et. al. (1980) – also standard used in this study, fluorine determinations

[2] Lucas, et. al. (1980) – Morocco, weathered

[3] Lucas et. al. (1980) – Calculated from author's data; intensely weathered

[4] Lucas et. al. (1980)

Table 29. Rare Earth Elements (REE) Content in Phosphorites - This Study and Average Values Obtained by Altschuler, 1980.

	AVERAGE PHOSPHATE THIS STUDY	AVERAGE PHOSPHATE[1]	AVERAGE[1] SHALE	←BREAKDOWN BY FORMATION OF "AVERAGE - THIS STUDY"→			
				EXSHAW[2]	SULF.[3]	RYMT.[4]	FERNIE[5]
	n=28	n=18	n=36	n=4	n=4	n=10	n=10
La[8]	180.0+	133.0	45.0	188.0+[6]	143.0+	188.0+	201.0+
Ce	156.0+	104.0	91.0	193.0+	172.0+	103.0	157.0+
Pr	100.0	21.0	10.7	100.0	100.0	100.0	100.0
Nd	139.0+	98.0	41.4	162.0+	83.0	149.0+	160.0+
Sm	30.9+	20.0	7.2	36.0+	18.6	30.9+	38.8+
Eu	6.9+	6.5	1.4	7.3+	4.2	7.6+	8.[illegible]+
Gd	-	12.8	6.0	-	-	-	-
Tb	3.9+	3.2	1.0	4.5+	2.3	3.4+	5.3+
Dy	35.0+	19.2	5.8	38.0+	20.0+	2[illegible].0+	53.0++[7]
Ho	7.5+	4.2	1.6	7.2+	5.0+	6.5+	11.3++
Er	-	23.3	3.8	-	-	-	-
Tm	1.9+	1.2	0.6	1.6+	1.4+	1.3+	3.2++
Yb	17.0+	12.6	3.6	14.0+	10.0	13.0+	30.0++
Lu	2.0+	2.7	0.7	1.6	1.1	1.3	4.0+

[1] Altschuler, 1980

[2] Exshaw Formation - Devonian/Mississippian

[3] Sulphur Mountain Formation - Triassic

[4] Rocky Mountain Supergroup - Permo-Pennsylvanian

[5] Fernie Group - Jurassic

[6] + Values above "average phosphorites - Altschuler"

[7] ++ Values above "average phosphorites - Altschuler" by 2 times

[8] All values in ppm via Neutron Activation - Gamma Ray method

"normal" amounts. Some of the differences between enrichment/depletion elements within this study compared to world averages has to do mainly with the Exshaw Formation. The Exshaw phosphorites show radically different quantities of several elements (i.e. As, Cd, Mn, Mo, Ni, Se, V, and Zn, Table 30) compared to the other formations. Thus, the Exshaw has had the effect of skewing the "average" values. Campbell (1980) found anomalously high values of uranium, nickel and zinc within subsurface samples of the Exshaw Formation, in particular near the base.

Cd, U, Y, lanthanons, Sr, Pb and Zn are all known to be able to substitute crystallochemically for calcium in the apatite lattice. Ag, Se, Mo, As, Ni, V, Zn, Cr, Cu, Cd and Sb are all known to be associated with organic complexing or adsorption within phosphorites (Altschuler, 1980). Depleted and normal elements are generally explained by their association with clay minerals, or by having too large or too small ionic radii to fit into the apatite lattice. The relative abundance of various elements in seawater, compared to shale seems to have little bearing on their abundance in phosphorites (Altschuler, 1980).

Table 30. Major, Minor and Trace Elements in Phosphorites of This Study and Average Values Obtained by Altschuler, 1980.

TRACE/MINOR[3]	AVERAGE[1] SHALE	ALTSCHULER, 1980 AVERAGE[1] PHOSPHATE	AVERAGE[1] ENRICHMENT DEPLETION	EXSHAW n=4	RYMT n=10	SULF n=4	FERNIE n=10	AVERAGE PHOSPHATE[2] THIS STUDY n=28
Ag	0.07	2.0	30.0+	3.0	2.0	2.0	2.0	2.07
As	13.0	23.0	N	156.0	13.3	14.6	24.5	52.1+
B	100.0	16.0	6.0+	-	-	-	-	-
Ba	580.0	350.0	N	694.0	477.0	1220.0	1521.0	978.0N
Be	3.0	2.6	N	-	-	-	-	-
Cd	0.3	18.0	60.0+	63.0	16.0	14.0	26.0	30.0+
Co	19.0	7.0	3.0-	23.9	24.4	12.2	18.0	19.6N
Cr	90.0	125.0	N	105.0	192.0	48.0	113.0	115.0N
Cu	45.0	75.0	N	100.0	100.0	100.0	100.0	100.0
Ga	19.0	4.0	5.0-	30.0	30.0	30.0	30.0	30.0
Hg	400.0	55.0	7.0	-	-	-	-	-
Li	66.0	5.0	13.0-	-	-	-	-	-
Mn	850.0	1230.0	N	58.0	238.0	335.0	112.0	186.0-
Mo	2.6	9.0	4.0+	114.0	25.0	46.0	46.0	58.0+
Se	0.6	4.6	8.0+	27.7	8.9	8.5	9.2	13.6+
Sn	6.0	3.0	2.0-	100.0	100.0	100.0	100.0	100.0
Sr	300.0	750.0	2.0-	484.0	370.0	471.0	753.0	520.0N
Tl	4600.0	640.0	7.0-	1500.0	500.0	1900.0	1500.0	1600.0-
U	3.7	120.0	30.0	44.9	30.8	26.5	35.5	34.4+
V	130.0	100.0	N	333.0	121.0	212.0	65.0	183.0N
Y	26.0	260.0	10.0+	-	-	-	-	-
Zn	95.0	195.0	2.0+	1610.0	63.0	195.0	230.0	525.0+
Zr	160.0	70.0	2.0-	375.0	344.0	380.0	392.0	373.0+
Others								
Sb	-	-	-	55.1	1.04	3.38	1.28	15.2
Br	-	-	-	3.0	3.2	4.5	5.6	4.1
Cs	-	-	-	3.0	1.3	1.7	1.9	2.0
Cl	-	-	-	ND	ND	ND	ND	-
Au	-	-	-	0.008	0.005	0.008	-	
Hf	-	-	-	1.97	3.42	6.03	3.84	3.82
In	-	-	-	ND	ND	ND	ND	-
I	-	-	-	ND	ND	ND	ND	-
Ir	-	-	-	0.02	0.01	0.02	0.01	-
Nb	-	-	-	ND	ND	ND	ND	-
Rb	-	-	-	53.3	12.0	30.0	25.2	30.1
Ta	-	-	-	1.02	1.8	0.80	0.66	1.07
Th	-	-	-	7.75	1.94	9.45	7.85	6.75
W	-	-	-	87.0	270.0	85.0	110.0	138.0
Majors								
Al	-	-	-	3.26	0.55	1.87	1.93	1.90
Ca	-	-	-	13.5	21.5	19.2	21.7	19.0
Fe	-	-	-	3.42	0.86	0.80	1.30	1.60
MG	-	-	-	0.52	1.2	4.0	0.65	1.59
K	-	-	-	2.4	1.0	1.2	1.0	0.0
Na	-	-	-	0.40	0.24	0.53	0.31	0.37
S	-	-	-	ND	ND	ND	ND	-

N = Normal

ND = No data

[1] Altschuler, 1980, Enrichment (+)= 2 x Average Shale, Depletion (-)= 1/2 or less Average Shale

[2] (+)=Enrichment 2X "Average Phosphorite", (-)= Depletion 1/2 or less "Average Phosphorite" (Altschuler, 1980)

[3] All values in ppm, except Majors - in % by Neutron Activation - Gamma Ray Counting

III. GEOLOGY OF ALBERTA-BRITISH COLUMBIA PHOSPHATE DEPOSITS

This section will outline the general stratigraphic, mineralogy and depositional environments of phosphate deposits in Alberta and southeastern British Columbia.

A. Stratigraphic Setting

The stratigraphic setting of the four main phosphate-bearing units: Exshaw Formation, Rocky Mountain Supergroup, Spray River Group and Fernie Group is outlined in this section.

Exshaw Formation

Members and Beds

The Exshaw Formation as described by Harker and McLaren (1958) consists of an upper limestone member, a lower shale member and a thin basal sandstone member. Macqueen and Sandberg (1970) recognized only an upper calcareous siltstone unit and a lower black shale unit. The three members of Harker and McLaren (1958) and five mappable horizons or beds are recognized in the present study (Fig. 7 Plate 1D).

The Basal Sandstone Member (BSM) disconformably overlies the Palliser Formation over much of the area from north of Crowsnest Pass to Willmore Wilderness Park (Fig. 27). In most sections this unit is 10-20 cm thick, and nearly always is overlain by a 2 to 30 cm (Section 76) bentonite bed (BBB Fig. 7). Lithologically the unit varies from a siltstone to a pebbly sandstone, with phosphate pebbles (0.5-3 cm in diameter), bone remains and occasionally pellets present. The unit weathers rusty brown, and is only slightly less resistant than the underlying Palliser Formation. Contact with the Palliser is everywhere sharp and slightly undulating, although no distinct erosional surface is evident. This unit gives off natural radiation readings in the 250-1000 cps range as detected by gamma spectrometer, the strongest response detected throughout the entire formation.[43]

The Lower Cherty Black Shale Member (LCBSM) contains the two principal phosphate horizons (LPH and MPH) plus an upper bentonite bed (UBB). It is areally distributed from Crowsnest Pass northward to Medicine Lake (Fig. 27). Erosion has probably removed the LCBSM from the area north of Medicine Lake and west of the Bosche Range. The LCBSM consists of a cherty black shale, fissile to thin bedded, non-calcareous (except near the upper contact with the ULM), recessive and yellowish-red weathering. It is very sparsely fossiliferous, not bioturbated at all, contains large (up to 1 m) diagenetic concretions and often shows synsedimentary depositional folding. The member yields natural radiation readings in the 150-500 cps range. Contact with the lower BSM is sharp though somewhat undulating. The upper contact with the ULM is somewhat gradational, becoming increasingly calcareous and silty up section.

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[43] With the exception of the phosphate horizons LPH and MPH

The thickness of the LCBSM in most places varies from 3 to 10 m, but thins to zero northward and thickens to a maximum of 43 m in a westward direction (Fig. 28). Cherty shales are predominant in the upper half of the member south of central Banff Park; north of Banff Park they are predominant in the lower half of the member.

The Lower and Middle phosphate horizons (LPH and MPH) are largely confined to the southern portions of the study area (Fig. 9). Both horizons are pelletal phosphorites, pellet-bearing sandstones or pelletal shales. Both are organic rich and show sharp upper and lower contacts within the LCBSM. Radiation readings generally rise to 200-600 cps at the LPH and MPH. Figure 27 illustrates the stratigraphic position and correlation of the LPH and MPH.

An upper bentonite bed (UBB) is found in scattered locations from Nordegg to the Crowsnest Pass. Folinsbee and Baadsgaard (1958) tried unsuccessfully to age date this bed exposed at Nordegg.

The Upper Limestone Member (ULM) has a wide distribution, ranging from the Bosche Range (Willmore Wilderness Park) south to the Northern High Rock Range in the Crowsnest Pass (Fig. 27). The member thickens from east to west, attaining a maximum thickness in the Bow Valley area of about 13 m (Fig. 29).[44] The ULM is a silty to argillaceous limestone or calcareous siltstone, weathers yellowish-orange, is

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[44] Macqueen and Sandberg (1970) claim that this member attains a thickness of greater than 40 m, at the type section of the Exshaw Formation along Jura Creek, near the town of Exshaw in the Bow River Valley. This author could find no such thickness in the vicinity south of the type section.

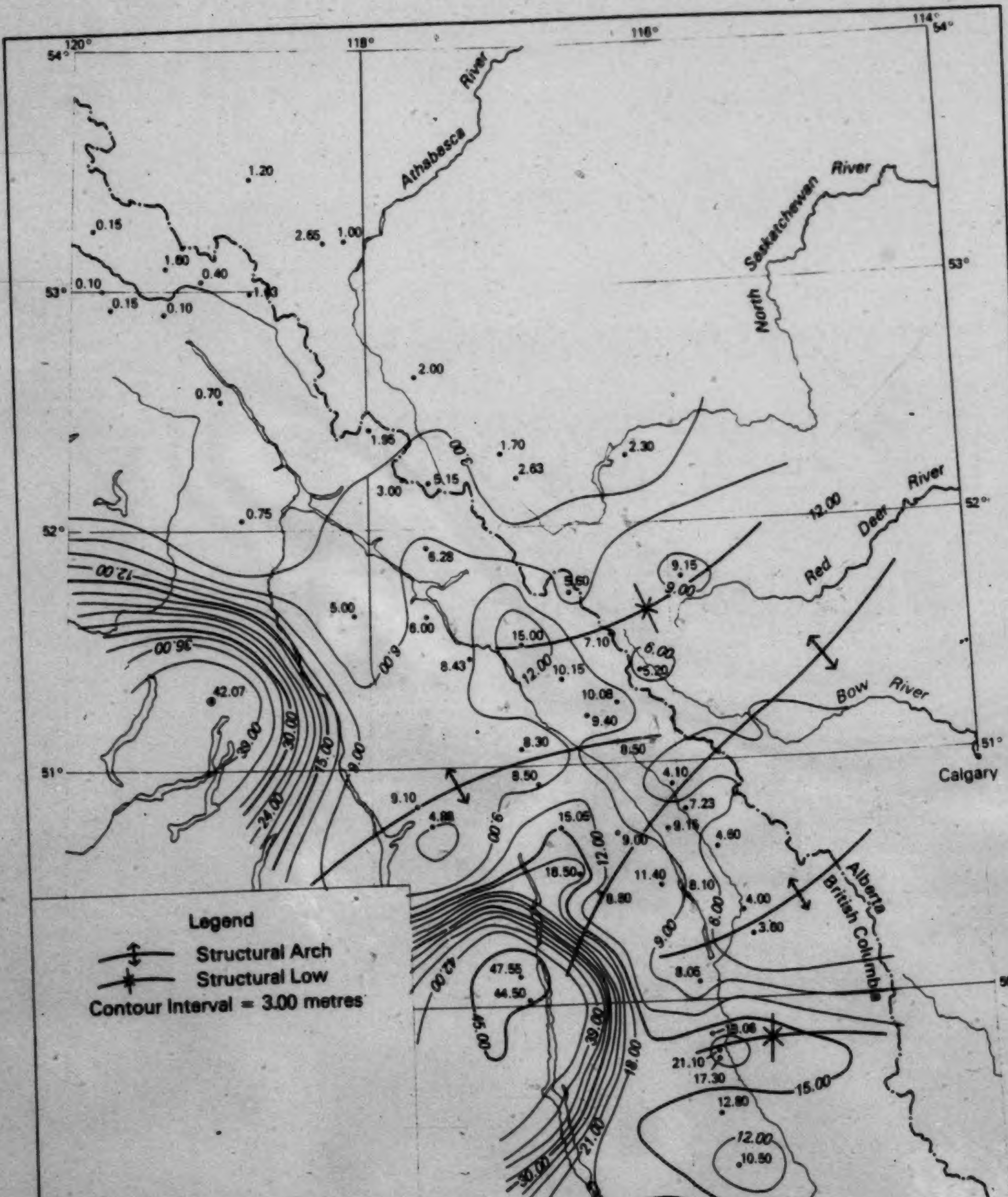
120°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Athabasca River
North Saskatchewan River
Red Deer River
Bow River
Calgary
Alberta
British Columbia
1.20
0.15
2.65
1.00
1.80
0.40
0.10
1.83
0.15
0.10
2.00
0.70
1.95
1.70
2.63
2.30
3.00
5.15
0.75
12.00
6.28
9.15
9.00
5.60
5.00
6.00
15.00
7.10
6.00
8.43
12.00
10.15
5.20
10.08
9.40
42.07
36.00
39.00
30.00
15.00
9.00
8.30
8.50
8.50
4.10
9.10
4.88
9.00
15.05
7.23
9.15
24.00
9.00
4.60
18.50
12.00
11.40
8.10
8.80
4.00
9.00
6.00
3.00
47.55
42.00
44.50
8.06
45.00
39.00
18.00
18.06
21.10
17.30
15.00
12.80
12.00
10.50
21.00
30.00
20.00
Legend
Structural Arch
Structural Low
Contour Interval = 3.00 metres
0
25
50 km

Figure 28. Isopach map of Lower Cherty Black Shale Member, Exshaw Formation — Palinspastically restored

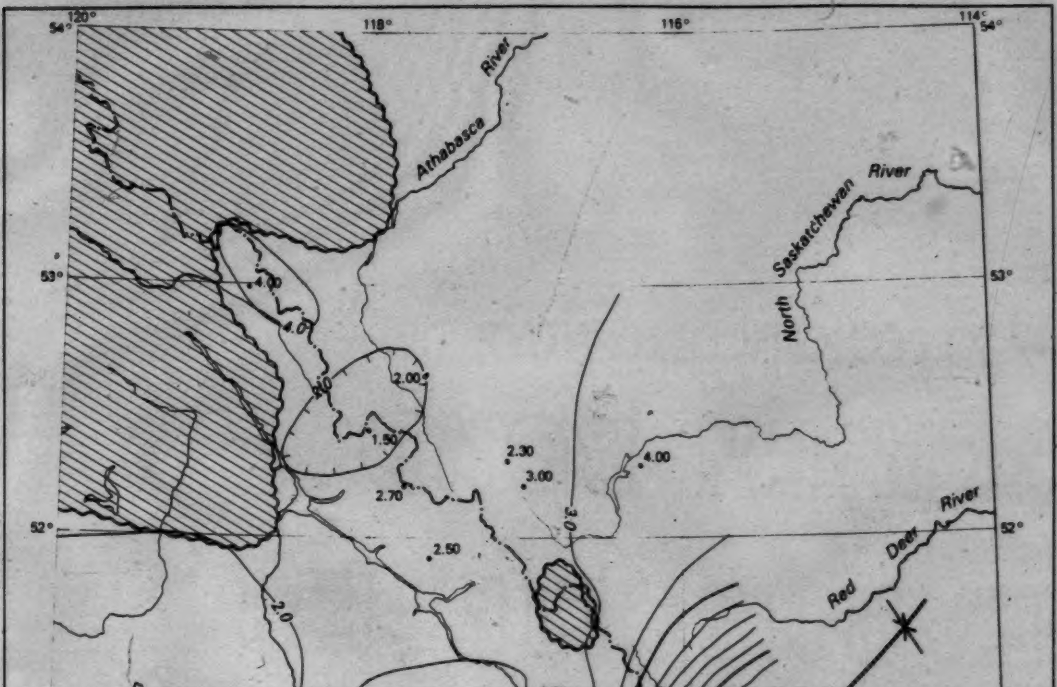
120°
54°
118°
116°
114°
54°
53°
53°
52°
52°
51°
51°
50°
49°
116°
114°
Athabasca River
North Saskatchewan River
Red Deer River
Bow River
Calgary
British Columbia
Alberta
4.00
4.0
2.00
2.0
1.50
2.30
3.00
4.00
2.70
3.0
2.50
2.0
1.50
2.50
2.50
5.00
12.00
15.00
13.0
12.0
13.00
12.20
12.00
10.00
8.0
10.0
6.0
4.0
3.00
4.00
4.50
4.00
7.20
6.00
4.50
4.50
4.80
6.20
5.0
2.20
4.0
5.00
3.0
2.70
Legend
▨ Member Eroded or Not Deposited
Contour Interval = 1.0 metre
0 25 50 km

Figure 29. Isopach map of Upper Limestone Member, Exshaw Formation — Palinspastically restored

resistant, is thin to thick bedded, contains abundant pyrite nodules up to 4 cm, and contains some *Rhynchonellid* brachipods (Plate 1D). Macqueen and Sandberg (1970) report numerous burrows and trails (*Scalarituba*), micro-cross laminations and flow rolls. Radiation readings are characteristically in the 100 to 150 cps range. The upper contact with calcareous black shale or interbed limestone / shales of the Banff Formation is generally sharp.

The Upper Phosphate Horizon (UPH) has been recognized at only two localitites (Fig. 27). It directly overlies the ULM as a bone or phosphate pebble conglomerate (Plate 1E).

Age and Correlation

The Devonian-Mississippian boundary has been placed by Macqueen and Sandberg (1970) somewhere in the middle of the LCBSM, based on conodonts and spores. The Exshaw Formation correlates to the Bakken Formation in the southeastern Alberta subsurface, and the Three Forks Formation in Western Montana. Regional correlation within Alberta is shown on Figure 27.

Rocky Mountain Supergroup

The Rocky Mountain Supergroup comprises all of the Permo-Pennsylvanian (Fig. 11). It is further broken down into the Spray Lakes Group (Pennsylnanian) and the Ishbel Group (Permian). All of the formations in these two Groups contain phosphates and so a brief stratigraphic description is given for each.

Spray Lakes Group

Tunnel Mountain Formation

The Lower Pennsylvanian Tunnel Mountain Formation consists of a very uniform, monotonous sequence of resistant, reddish-brown weathering, dolomitic sandstones and siltstones, with some of the sandstones approaching orthoquartzites. The formation characteristically shows medium and large scale trough crossbedding, is very clean and well sorted, is sparsely fossiliferous,[45] with some unidentified vertical burrows. It has a low (50 cps) natural radiation.

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[45] Most commonly phosphatic *Orbiculoidea sp.* brachiopods, *Spirifers*, and occasional bryozoans (McGugan and Rapson, 1962.)

The Tunnel Mountain Formation extends as far west as the the Elk Valley where it is thickest (>500 m), thining to about 18 m in the Livingstone Range. It extends northward to at least the Red Deer River, but is unrecognizable in the North Saskatchewan River area. The base of the formation is placed at the first occurrence of Mississippian dolomites, the top at the first occurrence of the Kananaskis Formation dolomites and / or phosphatic chert conglomerates (TIPC - this study). The lower contact is believed to be conformable in most areas [46], whereras a hiatus is suggested for the upper contact in some locations (McGugan and Rapson, 1962).

The Tunnel Mountain in Alberta has been correlated with the Tobermory, Storelk, Tyrwhitt, and Todhunter Formations (Fig. 11) in southeastern British Columbia (Stewart and Walker, 1980). Regional unconformities between the Todhunter / Tyrwhitt and Storelk / Tobermory are suggested by Stewart and Walker, citing evidence of phosphate pebble *Orbiculoidea*-bearing conglomerates at these contacts. The Tobermory is thought to rest unconformably upon the Mississippian Rundle Group in the Livingstone Range (Stewart and Walker, 1980).

Phosphate within the Tunnel Mountain in Alberta is found associated with intraformational conglomerates that may mark Todhunter / Tyrwhitt or Storelk / Tobermory regional unconformities as suggested by Stewart and Walker (1980). Natural radiation readings for the Tunnel Mountain Formation average 27 cps.

Kananaskis Formation

The Middle Pennsylvanian Kananaskis Formation consists of up to 70 m of light grey, resistant-weathering silty dolomites, dolomitic siltstones, orthoquartzites, cherty and calcareous sandstones, fusilinid bearing novaculitic cherts, the latter of which are stratigraphically diagnostic (McGugan and Rapson, 1979). Intraformational chert breccias are found throughout the upper parts of the Formation, in many eastern sections (Rapson, 1962), though few are reported to be phosphatic. Some of these chert breccias undoubtedly correspond to the KFIP horizon discussed in Part II. Marine fauna from the Kananaskis Formation include sponges spicules, bryozoans, the gastropod *Bellerophon*, and several *Spiriferid* brachiopods (McGugan and Rapson, 1979). A zone of *Skolithos*-type burrows is present at Section 392. The formation is thickest (70 m) near Fernie, British Columbia, thins by erosional truncation and by depositional attenuation to the east in the Livingstone / Highwood Ranges. It also thins northward, by erosional truncation and non-deposition, becoming unrecognizable north of the Red Deer River region.

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[46] Exceptions to this, such as in the Livingstone Range, are known.

The upper contact of the Kananaskis Formation with Permian strata is unconformable and is marked locally by the KIP horizon. In other places this contact shows straight concordant bedding and is marked by a sudden color change from the lighter colored Kananaskis strata to darker Permian rocks (McGugan and Rapson, 1961a).

The Kananaskis Formation is characterized by natural gamma radiation readings averaging in the 40-50 cps range, with the higher value including all phosphatic zones.

Ishbel Group

Johnston Canyon Formation

The Lower to Middle Permian, Johnston Canyon Formation is a series of recessive-weathering, dark colored, thinly and rhythmically bedded fine to medium grained clastic rocks (MacRae and McGugan, 1977). Phosphatic and argillaceous siltstones, silty carbonates, and dark spicular cherts are the most common lithologies. The formation becomes more carbonate and coarse clastic-rich northward. Thin intraformational phosphate pebble conglomerate beds are fairly common throughout the formation (see Section 295, Plate 1F). Pelletal phosphate zones are also found, particularly in southeastern British Columbia. MacRae and McGugan (1977) noted a general increase in phosphatic material toward the top of the formation.

The Johnston Canyon Formation is thickest in southeastern British Columbia (about 60 m) and thins rapidly to the east. The formation is erosionally truncated northward between the Clearwater and Red Deer Rivers, and is traceable southward to the U.S. border (MacRae and McGugan 1977). In the Telford thrust sheet in British Columbia, MacRae and McGugan (1977) recognized a threefold division of the formation: an upper cherty calcareous member, a middle silty phosphatic member and a lower sandy phosphatic member. This threefold division has not been recognized in Alberta, however.

The lower Johnston Canyon Formation contact is marked over most areas by the KIP conglomerate zone. The upper contact is generally well marked by the unconformable RCBP conglomeratic zone (Fig. 11), when overlain by the Ranger Canyon Formation. The upper contact is ill-defined, and is apparently conformable when the Johnston Canyon is overlain by sandy carbonates of Telford Creek Formation (southeastern British Columbia); here the contact is taken to be several thin cherty horizons (MacRae and McGugan, 1977).

The Johnston Canyon Formation contains sponge spicules, sparse fusulinid remains, *Orbiculoidea, Waagenoconcha, Crurithyris, Neochonetes* and *Spirifer* brachiopods, solitary corals and the trace fossil *Zoophycos* (Plate 2A) an index fossil for Permian age strata (MacRae and McGugan 1977). Phosphatic vertebrate bone remains are also occasionally seen in the KIP horizon.

Sedimentary and biogenic structures within the Johnston Canyon include intraformational phosphatic-clast and siltstone-clast conglomerate horizons, [47]rhythmically alternating siltstone and silty shale beds, and intense bioturbation at the base, but with very little bioturbation throughout the middle and upper parts, aside from *Zoophycus*.

The average natural radiation of the Johnston Canyon Formation varies from 33-46 cps but with local phosphatic zones reaching 200 cps or more.

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[47] Some of the siltstone clasts in the conglomerates have been reported by MacRae and McGugan (1977) to be curled up splinters of siltstone, suggesting former dessication and reworking.

Telford and Ross Creek Formations

The Telford and Ross Creek Formations are preserved mainly in the Telford Plate in southeastern British Columbia (MacRae and McGugan, 1977). The same authors describe possible Telford Formation carbonates in the Panther River area, though no fossils have been found to support this. Phosphates are only scantily known in these formations. The Telford Formation conformably overlies the Johnston Canyon and consists of resistant, thickly bedded, sandy, oolitic/pelletal, fossiliferous carbonates which are up to 240 m thick south of Telford Creek, British Columbia (MacRae and McGugan, 1977). The Ross Creek consists of recessive weathering, thin bedded siltstones, shaly siltstones, carbonates and cherts, reaching a maximum thickness of 150 m at Ross Creek (Fig. 12). Pelletal and nodular phosphate zones (up to 24% P_2O_5) have been noted throughout the formation, though no thicknesses are available (McGugan, 1972). Fossils within both formations include brachiopods, corals, crinoids, and bryozoa, all indicating a Middle Permian age (MacRae and McGugan, 1977).

The Telford-Ross Creek Formation contact is thought to be paraconformable with a thin chert conglomerate marking the contact (MacRae and McGugan, 1977). The upper contact of the Ross Creek with the Ranger Canyon Formation appears to be paraconformable and locally disconformable with the contact being marked by the RCBP horizon.

Ranger Canyon Formation

The Ranger Canyon Formation has a very wide lateral extent, extending from the Fernie Basin area in southeastern British Columbia, northward to the British Columbia Alberta border in Willmore Wilderness Park. Stratigraphic equivalents are known to occur as far north as the Yukon Territories (Fantasque Formation) and southward into the United States (Rex Chert Formation) (MacRae and McGugan, 1977). Westward the Ranger Canyon is not present in the Main Ranges, and eastward it is unrecognizable throughout most of the easternmost exposures of the Front Ranges. The formation is thickest in westernmost sections (Fig. 15).

Lithologically, the Ranger Canyon consists of resistant cliff forming, blue-grey colored, massively bedded cherts, cherty sandstones, sandstones and siltstones (Plate 2B). Dolomites, gypsum and phosphatic conglomeratics (RCBP zone) are also present to a lesser degree. The formation has been extensively silicified so as to make field determinations of original lithologies difficult. The RCBP consists mainly of breccio-conglomerates supported by phosphatic cement or matrix (Plate 2C). Clasts are frequently either chert or dolomite, fairly well rounded or very angular, and are up to 1 metre in size. One area around the southeast corner of Jasper Park contains clast-supported well rounded imbricated flat phosphate pebble conglomerate with a medium to coarse sand matrix at the RCBP zone (Plate 2D). The RCBP has been recognized as far north as the Tuchodi River, northeastern British Columbia (58 °28'N/ 123°58'W) by Bamber et al. (1968) as being a

> "...thin, irregular bed of shale containing numerous nodules and ? pebbles of phosphatic material".

The age of the Ranger Canyon has been tentatively set at Guadalupian, based on brachiopod evidence but as yet no fusilinids have been found (MacRae and McGugan, 1977).

North of the North Saskatchewan River the Ranger Canyon is overlain sharply and conformably (and further north, disconformably) by the Mowitch Formation. South of the river, the Ranger Canyon is disconformably and sharply overlain by the Triassic Spray River Group. The base of the Ranger Canyon is marked in most regions by the RCBP. The RCBP is in turn unconformably underlain by either undifferentiatied Carboniferous, Johnston Canyon, Ross Creek or (rarely) Kananaskis Formations, depending on the specific location (see Fig. 15).

Sedimentary and biogenic structures have largely been destroyed within the Ranger Canyon, by pervasive silicification. The trace fossils *Rosselia*, *Planolites beverleyensis* [4] and an unidentified "J" shaped vertical burrow are occasionally found within or immediately below the RCBP horizon (Plate 2F).

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[4] Trace fossil identification by G. Pemberton, Alberta Geological Survey

The most common feature observed is wavy and lenticular bedding. Cut and fill structures within the RCBP are common, having been eroded into the underlying formation with relief of up to 2.0 m observed, in some places (Plate 2E). Parallel laminations, current ripples, small scale cross stratification and heavy mineral laminations are also seen in these channel fill (?) deposits. The largest such channel was 3 m wide and 1 m deep.

The Ranger Canyon Formation has natural radiation readings averaging 45 cps excluding the phosphate zones, and 70 cps including phosphate zones.

Three phosphate zones have been identified within the Ranger Canyon: RCBP, RCIP, and RCUP (Fig. 11). The RCIP has been identified only in the Banff area in westernmost sections. The RCIP consists mainly of thin, lenticular, nodular or channel-type phosphate zones, with individual beds untraceable over any distance. The RCUP is found at the Ranger Canyon/Mowitch contact over a wide geographical area (Fig. 15). More detailed descriptions of all of these phosphatic zones appear in Part II.

Mowitch Formation

The Mowitch Formation is thought to disconformably overlie the Ranger Canyon over most of the study area, though some regions show apparent conformable contacts. This formation is thickest (67 m) in the Jasper Park-Willmore Wilderness Park regions and thins southward and eastward (Fig. 15) to a matter of a few tens of centimetres, south of the Red Deer River.

The Mowitch is lithologically very uniform, consisting of fine to medium grained, non-calcareous, thin to thickly bedded, pale yellow brown and slightly resistant, sub-angular quartz sandstones. Minor siltstone and shale beds occur towards the top of the formation. Silicified, lenticular cherty horizons are found scattered throughout the Mowitch, and in some sections in Willmore Park it becomes very difficult to distinguish the Mowitch from the Ranger Canyon, particularily when no erosional surface appears between the two (Plate 2B).

Sedimentary structures observed in the Mowitch include massive planar bedding, minor cross stratification, heavy mineral laminations, cut and fill structures near the top of the formation, silicified gypsum "knots", vugs and contractions features, and minor concretions. Biogenic structures found in the lower Mowitch show vertical "carrot" shaped (escape?) burrows, whereas toward the top of the formation, *Zoophycus* and *Spirophycus* become the dominate trace fossil. The Mowitch is assigned an Ochoan? age by MacRae and McGuggan (1977) based on *Neospiriferid* brachiopods.

The upper contact with the Triassic Sulphur Mountain Formation is frequently marked by the MUP zone and is generally thought to be disconformable. However, in some places (Sections 149 and 122) there is evidence to indicate that the contact may be conformable. At section 149 the Mowitch fines upward in grain size to a silty platy shale then upward into argillaceous siltstone of the lower Sulphur Mountain, seemingly without a break. The lower contact with the Ranger Canyon has been discussed; however, in a few localities in Willmore Park (Sections 97, 116 and 117) the Mowitch overlies undifferentiated Carboniferous strata. In this instance the MBP conglomeratic zone marks the contact. [49]

The Mowitch Formation is characterized by natural radiation readings in the 42-56 cps range.

Spray River Group

Sulphur Mountain Formation

The Sulphur Mountain has been divided into four main members by Gibson (1974): these are the Phroso, Vega, Whistler, and Llama (Fig. 17 Plate 3A and 3B). This formation is an easterly derived, fine grained clastic wedge sequence that thickens from east to west. It consists largely of a recessive-weathering sequence of grey to rusty brown dolomitic calcareous siltstones, and to a lesser degree sandstones, silty limestones, dolomite and shale (Gibson, 1974). The formation attains its greatest thickness of 496 m in the Elk River Valley, British Columbia (Gibson, 1974) and thins to a minimum of 23 m in the Livingstone Range of southern

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[49] As mentioned in Part II, the MBP horizon may be a time equivalent to all or some of the RCUP, RCBP, JCUP or many others.

Alberta. The age of the various members has been fairly well estabished, using ammonites and pelecypods (Gibson, 1974).

The Phroso Member is characterized by thin to fissile bedded, recessively weathering, reddish-brown colored, dolomitic and carbonaceous siltstones, argillaceous siltstones and silty shales. The basal 10m or so is frequently marked by organic-rich, very recessive weathering, dark grey to black silty shales (Plate 3A). At the base of this recessive unit lies the BPMP (Fig. 17), earlier described. The Phroso appears to disconformably overlay Permian or Pennsylvanian strata in most places. The PMIC horizon (Fig. 17) is found within the more resistant upper portions of the Phroso, and is probably not a single continuous zone but rather several lenticular lenses within the upper Phroso. The trace fossil *Palaeophycus heberti* is present at Section 243-Ribbon Creek, though biogenic structures, in general, do not seem overly abundant within the Phroso member.

The Vega Member is a sequence of rusty brown weathering, slightly more resistant (relative to Phroso), medium to thick bedded dolomitic siltstones, rhythmically interbedded, with very thin bedded to fissile siltstones (Plate 3A). The Phroso Vega Member contact appears gradational and is believed to be conformable. The Vega-Whistler contact is conformable but is possibly diastemic, and is marked by the LWMP zone (Fig. 17). In places where the Llama Member directly overlies the Vega, the contact is placed at a sharp color change from grey-reddish brown (Vega) to pale yellow-brown. Flow rolls, siliceous concretions, interference ripples, cross laminations, flute, groove and bounce casts all are present in the Vega Member. Phosphatic *Lingulid* shells are found in dolomitic horizons and burrows morphologically similar to *Arenicolites* are seen in some of the finely laminated siltstones.

Scattered occurrences of phosphatic fish remains and reworked pebbles as reported by Gibson (1974, 1968a) are grouped into the VMP zone , though probably represent several lenticular, discontinuous zones.

The Whistler Member is a recessive weathering sequence of thinly bedded, carbonaceous and argillaceous silty dolomites and dolomitic siltstones. Lighter grey dolomite laminations are typically seen interbedded with silty shale beds. The lower contact is marked by the LWMP (Fig. 17); and the upper contact with the Llama Member is marked by the UWMP or by the first appearance of medium to thickly bedded siltstones. Wavy, lenticular and flaser-type bedding are the most common structures seen. Biogenic structures do not seem to be present. A few ammonites have been recovered (Gibson, 1974), although the member as a whole is sparsely fossiliferous. The phosphate present within the LWMP, MWMP and UWMP (Fig. 17) consists mainly of oolitic pellets and ooliths, some pebbles and scattered bone remains.

The Llama Member is a resistant, cliff forming sequence of thin to thickly bedded, yellow brown, silty sandy dolomite and dolomitic siltstones. The overlying contact with the Whitehorse is generally sharp. Some intraformational dolomitic-clast conglomerates as described by Gibson (1975) probably correspond to the LMP zone in the present study study (Fig. 17). The Llama is conspicuously lacking in sedimentary or biogenic structures, the siltstone units typically being massive and structureless. Gibson (1975) has noted mottled bioturbated siltstones in the Llama Member from northeastern British Columbia and it is probable bioturbation also is present in the Llama in Alberta. The lack of any sedimentary structures suggests complete churning of the Llama sediments, the net result being an apparently structureless, massive unit. Some oolitic pelletal phosphorite zones are present in the LMP in the Kananaskis area.

The Whitehorse Formation

The Whitehorse Formation consists of the Starlight Evaporite, Brewster Limestone (locally) and Winnifred Members. The formation consists of a sequence of generally pale weathering, resistant, yellow and red interbedded carbonates, sandstones, siltstones, breccias and gypsum (Plate 3B). Intraformational conglomerates, corresponding to the WMP (Fig. 17), are reported from the Winnifred Member (Gibson, 1974). The Winnifred Member is confined to the region between Willmore Wilderness Park and the North Saskatchewan River, where it is disconformably overlain by the Fernie Group. South of the Bow River the Whitehorse is undifferentiated. Sedimentary structures in the Whitehorse include collapse breccias, boxwork solution textures, large scale cross stratification, and small cut and fill structures (Gibson, 1974). The Whitehorse is conspicuously lacking in fossils or biogenic structures.

Fernie Group

The Jurassic Fernie Group consists of 70 to 376 m of marine shales, limestones and sandstones. The Group thickens from east to west, in general. It is found throughout the Front Ranges area, primarily in major intermontane valley areas, its topographic expression being a result of the recessive nature plus the stratigraphic / structural control (Fig. 5, Plate 1A). The Fernie Group has been divided into several members and beds (Frebold, 1957), and the nomenclature adopted for this study is shown on Figure 19. Fernie strata unconformably overlay Triassic strata in most areas; however, in Southern Alberta they overlie the Pennsylvanian Tunnel Mountain Formation. The Group as a whole has been well dated using ammonite zonation (Frebold, 1957, 1969) although there are gaps of significant time intervals that cannot be accounted for (Fig. 19). It is not known if this is a lack of collected index fossils or whether these gaps represent true hiatuses, or periods of very slow sedimentation.

The Fernie Group crops out in a fairly narrow band extending from the Crowsnest Pass area northward beyond the study area in Willmore Wilderness Park (Fig. 20). Its presence is not known west of the Front Ranges of the Canadian Cordillera, although Jurassic age strata, primarily volcanics, are found throughout central British Columbia. The Fernie Group extends eastward into the subsurface, where it thins, both depositionally and by post-Jurassic erosion.

The regional stratigraphy of the Lower Jurassic portion of the Fernie Group is shown by a series of columnar sections in Figure 22. The areal extent of Lower Jurassic phosphate-bearing strata is confined to westernmost exposures of the Group (Fig. 20), those being primarily Sinemurian in age. Middle Jurassic phosphates are confined to the Rock Creek Member. The Rock Creek Member, as a coarse clastic unit, extends from the Athabasca River south to Crowsnest Pass, although phosphate-bearing Rock Creek appears to be further limited to easternmost exposures of the Fernie Group.

Sinemurian-age strata consists of two main lithofacies: an eastern carbonate-chert assemblage and a western fine grained clastic phosphatic facies (Fig. 22). The eastern facies is represented by the Nordegg Member in outcrop (Nordegg Formation in the subsurface), and consists of up to 50 m of medium to thickly bedded limestones, cherty and sandy limestones, chert, sandstones, dark carbonaceous shales, breccia beds and coquina beds (Plate 3D). The western phosphatic facies (Plate 3C) consists of up to 10 m of thinly interbedded carbonaceous / calcareous shales and limestones, mudstones, pelletal phosphates, and up to seven thin bentonite seams. Phosphate in the Sinemurian age shale is mainly concentrated in the eastern facies (in particular the BFP zone) which generally marks the oldest Jurassic strata present. Phosphate also occurs to a much lesser extent in the Nordegg Member, western facies (NMLSP, NMP and FOP, see Part II). Sedimentary structures are generally lacking in Sinemurian strata, and individual bed contacts are generally sharp. Graded and poorly sorted homogenous sandstone beds are occasionally present within these predominantly shale sequences of the eastern facies. The BFP is generally structureless, with occasional phosphate intraclast horizons being present (Plate 3F). Biogenic structures are also generally lacking in Sinemurian strata, with a few unidentified horizontal burrows present in the Nordegg, one occurrence of a burrow with a *Thalassinoides* morphology in the BFP and one *Paleodictyon* trace from Sinemurian age shales.[50] Hard bodied fossils are abundant in the Sinemurian strata with the index fossil ammonite *Arnioceras sp.* present at several localities of the BFP (Plate 3E). *Gryphae, Oxytoma, Pleuromya, Ostrea, Pectens and Camptonectes* invertebrates are also common (Frebold, 1957). Ribs, miscellaneous bones, vertebrae (*Ichthyosaurous ?* pers. comm. C.R. Stelck), are particularly abundant in the Lower Sinemurian.

The Sinemurian strata are generally very recessive weathering and are characterized by natural radiation readings averaging from 50 cps (Nordegg Member) to 150 cps (non-phosphatic units) to greater than 300 cps in phosphatic horizons. The lower contact with Triassic, or in some cases, Permo-Pennsylvania strata is invariably sharp and disconformable. The BFP commonly marks this contact, as pelletal phosphorites up to 2 m thick (Plate 3F), or as a 10-20 cm thick phosphatic conglomerate or sandstone (Plate 4A). Where the BFP (as described above) is not present the contact is generally marked by highly radioactive shales (>200 cps) that are often weakly phosphatic. This lower contact is easily picked at most localitites, except in the Crowsnest Pass area, where dark colored, recessive phosphorites (BFP) overly dark colored, recessive siltstones of the Sulphur Mountain Formation. With care, the two can be readily distinguished. The upper contact with the Poker Chip Shales or the Red Deer Member is sharp where the entire Sinemurian is represented by the thin phosphatic sandstone (BFP). However, where the Nordegg or Nordegg equivalent is developed, the upper contact is more gradational. In the absence of reliable index fossils, this contact was taken to coincide with the uppermost occurrence of chert, or the disappearance of multiple bentonite seams.

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[50] Identification of *Paleodictyon* by G. Pemberton, pers. comm.

The Pleinsbachian Red Deer Member and the Toarcian Poker Chip Shales have a wide areal extent, generally somewhat larger than the Nordegg and Nordegg equivalent strata. In many eastern exposures the Sinemurian strata is either absent or only present as the thin BFP zone, so that the Poker Chip Shales are directly overlying Triassic or Permo-Pennsylvanian strata. Pleinsbachian-age rocks have been identified positively by index fossils in a small region around the Red Deer and Clearwater Rivers (Frebold, 1969). The upper contact of the Poker Chip Shales is sharp and distinct, with the dark, organic, calcareous interbedded limestones and shales of the Poker Chip Shales abruptly replaced by non-calcareous, rusty weathering, (pyritic), fissile shales of the Rock Creek Member (Plate 4B). Lithologically the Poker Chip Shales is a uniform series of very thin to thinly interbedded dark organic shales and microcrystalline limestones. Sedimentary and biogenic structures are generally not present. Invertebrate fossils most commonly encountered include the index ammonite - *Dactylioceras, Belemnites, Lima, Ostrea, Pseudomonotis, Camptonectus and Antolleum.*[51] One locality (Section 273) revealed a fossil fish jaw bone, tentatively identified as *Bellonostomus.*[52] Phosphate is present within the Red Deer Member (RDMP), the Poker Chip Shales (TPCP) in the Fernie basin area, and at one locality (Section 190) at the Poker Chip Shale/Rock Creek Member contact. The Poker Chip Shales are characteristically recessive weathering and normally contain natural radiation reading of about 150 cps.

Within the Middle to Upper Jurassic, phosphate is present only within the coarse clastic facies of the Rock Creek Member. This clastic facies of the Rock Creek Member is found throughout the Middle Fernie in the Front Ranges and into the subsurface. The upper contact with Bathonian or Callovian-age strata is not distinct and is based, lithologically, on a transition from reddish-brown weathering shale to light grey weathering shale. Lithologically the Rock Creek Member, shaly facies, consists of dark grey to black, reddish brown weathering pyritic fissile shales with some interbedded, arenaceous belemnite-rich limestones. The coarse clastic facies of the Rock Creek Member consists of interbedded sandstones, siltstones, and some shales (Plate 4C). Figure 30 shows the problem of detailed correlation of the Member, over great distances, with only widely scattered sections. Phosphate is found most commonly as nodules, though occasionally oolitic pellets, at the uppermost and lowermost contacts of the coarse clastic facies of the Rock Creek Member (FRCUP and FRCLP zones). Figure 30 shows how the FRCUP zone is found predominantly in the northern region whereas the FRCLP predominants in the south.

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[51] Fossil identification by C.R. Stelck, Department of Geology, University of Alberta

[52] Identification by M.V. Wilson, Department of Zoology, University of Alberta

Invertebrate fossils are very common within the coarse clastic facies of the Rock Creek Member and include: *Telocesas, Sonninia* (index ammonites), *Rhynchonella, Cucullaca, Inoceramus, Oxytoma, Cardinia, Trigonia, Camptonectes, Entollium, Pleuromya, Arctica* and *Belemnites* (Frebold, 1957). Biogenic structures include *Gyrochorte, Rhizocorallium* and *Planolites montanus* [53], all from the Cruziana icnofacies (Plate 4E). Belemnites are the most common fossil found within the Rock Creek Member and are often found concentrated in calcareous, arenaceous horizons as "Belemnite Battlefields" (Plate 4D). The Rock Creek Member, a coarse clastic facies attains its greatest thickness in the Cadomin-East Jasper Park area (31 m), and near the type section at Rock Creek in the Crowsnest Pass region (25 m). The correlations from sections 324 to 367 and 286 to 283 on Figure 30 illustrate how both westward and eastward increase in sandstone versus shale can occur. The clastic facies seems to thin between Cadomin and Crowsnest Pass (north-south direction) and changes to the shale facies. Springer et al. (1964) found the Rock Creek Member, in general, to become more argillaceous in a westward direction, and more arenaceous in an eastward direction. based on subsurface data.

An excellent discussion of the remainder of the Fernie Group, not containing phosphate, can be found in Frebold, 1957.

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[53] Trace fossil identification by G. Pemberton, Alberta Geological Survey

B. Mineralogy and Petrology of Phosphates

General

Most phosphorites throughout the world are of the carbonate-fluorapatite variety; francolite (Cook, 1976). The Western U.S. Phosphoria Formation deposits are classed as primarily fluorapatite with some carbonate substitution (Gulbrandsen, 1967). Most of the phosphorites in this study appear, based on microprobe chemical analysis and x-ray diffraction, to be transitional between pure fluorapatite and pure francolite. The mineralogy of phosphates, within this study, was determined using standard petrographic, x-ray diffraction, scanning electron microscopic and most importantly, electron microprobe techniques.

X-ray diffraction (XRD) revealed the presence of fluorapatite or hydroxyapatite in all samples. The "peak-pair" method (Gulbrandsen, 1970) showed that all of the phosphates examined contained 0.5 to 3.0% CO_2, CO_2 being a reflection of carbonate replacement in the apatite. Representative samples and their respective CO_2 contents from all phosphates in the present study (Table 28) have an average CO_2 content of 1.66 weight percent (n = 16).[54] This compares closely with Gulbrandsen's (1970) findings of 1.8 weight percent for the Phosphoria Formation in the Western U.S.A.

Electron Microprobe investigations, in this study, show the characterisitc chemical properties of the phosphorites in this sudy compared to several theoretical and other world wide deposits (Table 28). When all samples, from this study are considered, it appears that with respect to F/P_2O_5, CaO/P_2O_5, CO_2, F, Na_2O contents the phosphorites more closely resemble fluorapatite. When considered with respect to their CaO, P_2O_5 and MgO, contents the phosphates in this study more closely resemble francolite. It would therefore appear that some CO_3^{-2} substitution has taken place, a conclusion supported by the XRD work. Chemical analysis, as determined by microprobe, of all samples via geolołocal period and by petrographic lithotype appear in Appendix 7.

Closer inspection of Table 28 suggests that some of the lithotypes or time periods produced phosphorites more closely resembling true fluorapatite (e.g. Precambrian phosphorites) while others more closely approximate the francolite end member (e.g.

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[54] Excluding the single Precambrian phosphorite, considered separately

intraclasts). Petrographic work suggests the presence of dahllite, however none was detected with x-ray diffraction or measured with the microprobe.

Exshaw Formation

Mineralogy

The mineralogy of phosphorites from the Exshaw Formation very closely resemble fluorapatite with respect to the F/P_2O_5, CaO/P_2O_5 ratios, and CO_2, F, Na_2O and MgO contents (Table 28). Deviations from the ideal occur in the individual CaO and P_2O_5 contents, being somewhat depleted. This depletion may be a weathering phenomenon. A brief petrographic description of each of the members of the Exshaw Formation follows

Petrography

The Basal Sandstone zone (BSM) consists primarily of quartz, orthoclase feldspar, calcite, dolomite, flourapatite, illite, jarosite and pyrite as determined by XRD. Andradite ($Ca_3F_2(SiO_4)_3$) was tentatively identified from an argillaceous equivalent to the BSM. The member is characteristically angular to subangular, very fine to very coarse grained, poorly sorted, illite / carbonate / hematite cemented sandstone. The phosphate material consists of nodules (up to 2 cm), bone fragments, structureless, nucleated and rimmed pellets, intraclasts - often composed of aggregated pellets - and some indication of microsphorite (Plate 5A).[55] Most locations of the BSM show sharp micro-erosional / scour surfaces with the underlying Palliser Formation, with volcanic ash, pebble horizons, microsporite or sandstone immediately overlying this contact. Gradational contacts of Palliser limestone to cherty phosphatic limestone to microsphorite are present, though less common than the sharp contact types. Hematite is very common throughout the horizon, often as detrital grains and less commonly as a fine grained cement. Replacement features include feldspars altered and replaced by sericite and calcite and calcite replacing phosphate. Perhaps the most important texture observed was detrital grains of hematite-rich pisolitic structures at Section 154. Structures very similar to these have been described as lateritic hardpan deposits, characteristic of subaerial weathering horizons (Scholle, 1979). The BSM phosphates therefore show evidence of primary authigenic microsphorite precipitation, phosphatization of cherty limestones of the Palliser Formation and reworking of phosphatic material into sandstones and conglomerates.

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[55] See Table 2 for descriptions and examples of phosphate petrographic lithotypes.

The Lower Cherty Black Shale Member (LCBSM) consists of very thinly bedded siliceous / chertified shales with quartz, orthoclase, and illite predominating and pyrite, calcite, jarosite and dolomite present in minor amounts. Carbonates become more abundant as the Upper Limestone Member contact is approached. The origin of the abundant siliceous material is not certain but does not seem to be related to siliceous clastic material. Some evidence of sponge spicules is present. The Lower Sappington Member, that is laterally equivalent to the LCBSM and is exposed in the Crowsnest Pass area (Fig. 27), does appear to have been a spicule rich chert, now largely replaced by sparry calcite. The LCBSM is organic rich and MacQueen and Sandberg (1970) report values up to 9.0% (normal values 0.6-4.7%) with values decreasing upsection.

The Lower and Middle phosphate horizons (LPH and MPH) exposed near Crowsnest Pass, contain mostly pelletal phosphates, with nucleated and oolitic varieties predominating south of Crowsnest Pass and structureless / elongated varieties predominating north of the Pass. Both regions also contain structureless nodules and intraclasts. The northern region pellets are characteristically bleached, very tightly compressed, flattened, show moderate sorting, are 0.3 to 0.8 m in size, and are surrounded by an organic-rich argillaceous matrix (Plate 5B). The southern region pelletal phosphorites are characterized by: pellets cored with other smaller pellets or with detrital quartz / hematite / bones, having a well rounded shape, are moderately to well sorted, matrix free, 0.2 to 2.0 mm in size, very loosely packed to floating and cemented with chert and less commonly phosphate (Plate 5C). All of the lithotypes are medium to dark brown in plain polarized light (believed to be a reflection of high organic contents) and are virtually isotropic under crossed nicols. The LPH and MPH therefore show strong evidence of forming authigenically as perhaps phosphatic gels, in the interstital muds, immediately below the water / sediment interface. This would seem to be especially true of the phosphates north of the Crowsnest Pass. Those south of the Crowsnest Pass are more fully developed, are well winnowed, show nucleated pellets, all of which suggest a more active energy environment.

Phosphate from the MPH in the Central Rocky Mountain area (Fig. 9) is rare but when present is as structureless, and nucleated pellets and bone fragments within well sorted, sub-angular to angular, very fine to fine grained, calcite cemented, pyrite rich sandstones. The percentage of phosphatic material rarely exceeds 5% P_2O_5 on a bulk analysis.

The Upper Limestone Member was not examined petrographically, however MacQueen and Sandberg (1970) report this member as a calcareous siltstone to silty limestone containing quartz, feldspar, chert, detrital and matrix dolomite with minor amounts of siderite, anhydrite, gypsum, pyrite, apatite, illite, kaolinite, and chlorite. The clastic component reaches up to medium sand in size, is generally angular to subangular, poorly sorted, and occasionally contains spicule rich shale intraclasts. Phosphatic bone and / or shell remains are present, but not common.

The Upper Phosphate horizon (UPH) consists, at the northern location (Section 37), of a conglomeratic mixture of quartz, dolomite, pyrite, phosphatic bones, nodules, intraclasts, structureless, elongated and nucleated pellets, microsphorite intraclasts and C1 type phosphate cements (Table 2, Plate 5D). At the southern locality (Section 191) the phosphate occurs as bone, elongated pellets, intraclasts and some C3 type cement (Table 2) within an organic rich, well sorted siltstone. Glauconite appears to be replacing some of the bone material at this location. The UPH is therefore seen primarily as a reworking of previously precipitated phosphatic materials into a pebble conglomerates. Some replacment by phosphate of an original unknown cement within the siltstones also apparently took place.

Spray Lakes - Ishbel Groups

Mineralogy

The mineralogy of phosphates within the Spray Lakes and Ishbel Groups is again transitional between pure fluorapatite and pure francolite (Table 28). Chemically the phosphates, more closely approach fluorapatite in most of the diagnostic indicators, except P_2O_5 content - where francolite is more closely approached. Petrographically "francolite cement" was identified in many samples as light yellow brown (crossed polars), creamy light brown (plain light) and fibrously radiating. Examination of Table 28 for the chemical details of "francolite cement" as determined by the microprobe shows very little difference between it and the other "primary cement". "Francolite cement" as used in this context is thought to be a recrystallized form of the other C1, C2 and C3 type cements. The C1 to C3 cements are dark brown (plain light), nearly isotropic under crossed polarized light, and show no discernable crystal structure. This material is the cryptocrystalline fluorapatite previously known as "collophane". Scanning electron microscopic examination shows the "collophane" type fluorapatite to be extremely finely crystalline forms in the 100 to 400 nanometer size range (Plates 5E and 5F). Conversely "francolite" tends to form lath-like euhedral crystals of a much larger size range (Plate 6A).

Petrology

Tunnel Mountain Formation

The most common phosphate petrographic lithotype in the Tunnel Mountain Intraformational (TMI) phosphates is as scattered bone remains, and occasionally as intraclastic pebbles (I2) (Table 2). The phosphates are usually found in thin chert pebble conglomerates or within well sorted, subangular to subrounded, fine to very fine grained, dolomitic, quartzose sandstone.

The Tunnel Mountain Interformational Phosphates (TIP) consists mainly of phosphate pebbles (I2, Table 2) and pellets, less commonly nodules, bones and cement. The phosphate pebbles are generally well rounded, up to 2 cm in size, are composed of the recrystallized "francolite" type phosphate cement or the C1 to C3 type primary cements. Pebbles are often multiple aggregates of former pellets, clastic debris and sponge spicules. Chertification has been a very widespread phenomena throughout all of the Spray Lakes Group (Rapson, 1962) and as such some phosphatic materials, particularly bones, have been replaced by chert or chalcedony. These pebble beds, also contain chert pebbles and are almost always cemented with chert or chalcedony. Well sorted calcite cemented sandstone containing scattered structureless pellets (P3) are encountered in the easternmost Livingstone Range. These pellets are characterized by being organic rich, 0.2 to 0.3 mm in size, rounded to well rounded and show some evidence of calcite replacement. Nodules up to 3 cm in size, are also present.

The Tunnel Mountain Formation phosphates tend to be reworked and in some cases re-crystallized phosphatic material.

Kananaskis Formation

The Kananaskis Interformational Phosphates (KIP) are characterized petrographically by a predominance of C1 or C2 type cements within pebble conglomerates or fine to medium grained sandstones. Francolite cement, microsphorite intraclasts (I3), pebbles (I2) and I1 type intraclasts are present, though much less commonly (Plate 6B). The phosphate cement has extensively replaced abundant sponge spicules throughout most of the samples studied. Carbonate has also replaced sponge spicules to a lesser degree. The sandstone or conglomerate hosting the phosphate range from poorly to well sorted with clasts that are angular to rounded. Chert and dolomite comprise the main clastic material within these sandstones and conglomerates. The phosphate pebble material is generally composed of reworked detritus free C1 to C3 type cements, are well rounded and are up to 2 cm in size.

The Kananaskis Formation associated phosphates tend to be reworked material and phosphatized preexisting material, chert in part, and possibly recrystallization of an original primary phosphate cement.

Johnston Canyon Formation (JCIP)

The Johnston Canyon Intraformational phosphates (JCIP) consists mainly of diagenetic nodules, intraclasts, quartz cored pellets and less commonly as patches of C3 type cement (Table 2). The nodules are usually composed of francolite type cement with numerous clastic quartz grains "floating" in the cement. The grain size and mineralogy of material within the nodule is identical to that outside the nodule, suggesting slow replacement of original quartz overgrowth cement with francolite cement, leaving the clasts apparently "floating". Hematite and/or manganese rims are sometimes present, part way around the nodule. Intraclasts are often found as thin (<10 cm) horizons showing scour bases, and are composed largely of aggregates of quartz cored pellets or structureless pellets (Plate 6C). Some intraclasts are composed of detritus free primary cement. Siltstones and very fine grained sandstone, both being well sorted and angular, are the typical "host rocks" for these phosphorites. Carbonate is apparently replacing an earlier clay? cement in these fine grained rocks. Pelletal phosphorites have been reported by several companies studying this stratigraphic zone (Cominco Ltd., J. Hamilton, pers. comm.).

Johnston Canyon Formation (JCUP)

The Johnston Canyon Upper phosphate zone (JCUP) is, as mentioned previously, likely equivalent to the RCBP zone, however where this horizon has been identified, no overlying Ranger Canyon Formation is present and the JCUP directly underlies the Triassic Sulphur Mountain Formation. The main petrographic phosphates lithotypes present are as C2 type cements, and francolite (C6) type cements, though structureless and oolitic pellets, bones and shells, nodules, and intraclasts can all be found to a lesser degree (Plate 6D). The host rock is generally a very fine grained sandstone, whose clasts generally appear to be "floating" in the phosphate cement. Most of the clastic quartz show pitted and etched surfaces suggesting dissolution and corrosion. It appears that these sandstones have had their orginal cement replaced by phosphate cement, and in so doing have had their surfaces pitted by an active chemical environment. Little evidence remains to suggest what the original cement may have been except perhaps an earlier phase of phosphate or a siliceous cement. An early siliceous cement is suggested by the presence of numerous partially and wholly phosphatized sponge spicules and chert and quartz clasts (Plate 6D). Echinoderm and other unidentified fossils are also present. One sample examined looks very much like a former spicule-rich chert, now nearly completely replaced by phosphate. Calcite is seen to be in turn replacing phosphate in some places throughout most samples. Pelletal phosphates within the JCUP are generally in the 0.2 to 0.3 mm size range, are rounded, well sorted, organic rich and often appear dark brown in plain polorized light in contrast to the cement areas (Plate 6D). Nodules that are present in otherwise unphosphatized sandstones contain quartz detritus apparently much smaller than the host lithology. This however may be due to the dissolution process alluded to earlier. Pyrite is very common in these nodules as an accessory mineral. Intraclasts within the JCUP tend to look very much like reworked and transported C2 type cement phosphates described earlier in the paragraph. Intraclasts are found in well sorted, fine grained, otherwise non-phosphatic sandstone, and tend to be a minor component in the rock.

Ranger Canyon Formation (RCBP)

The Ranger Canyon Basal Phosphate zone (RCBP) was the zone most extensively studied, as it would appear to have the best potential for future development. Phosphate within the RCBP is overwhelmingly of the C1, C2, C3 and francolite (C6) cement types. Pelletal varieties generally comprise less than 10% of the lithotypes, and within this group the structureless (P3) varieties greatly exceed, in abundance, the oolitic (P1) and nucleated (P2) forms. Microsphorite (C4) is exceedingly rare and was only seen in two possible cases. Intraclasts, nodules and phosphatized fossils together comprise about 20% of the lithotypes.

Phosphate pebbles were deposited as a bimodal phosphate pebble conglomerate (RCBP) occuring in the central region of the study area (Fig. 34). These pebbles are detritus free, clast supported in a well sorted medium sand matrix, are flattened, elliptical and show imbrication, and are up to 2 cm in size (Plate 2D).

The breccio-conglomerates "hosting" the phosphate tend to have unordered fabrics, often - though not always - are matrix cement supported, show no grading, are polymodal and clasts are rounded to angular - sometimes within the same rock (Plate 2C). Clast composition consists of chert, dolomite, sandstone and less commonly phosphates. Clast size varies from 1 to 50 cm. The matrix to these conglomerates consists mainly of sand size chert, quartz, sponge spicules, phosphate pellets, bones and other minor accessory minerals (Plate 6E). Sandstone "host" rocks tend to be fine grained, well sorted, show pitted quartz and chert clasts, clasts are "floating", and are cemented with phosphate (Plate 6F). This fine clastic facies tends to be concentrated in the southwestern part of the study region (Fig. 34). Dolomites are the host rock in a small area in the southwestern part of the region (Fig. 34). When dolomite is the "host" rock phosphate cement is preferentially found in silty quartz laminae or aggregates that contain higher porosity than the very fine grained dolomite.

The phosphate cements (C1, C2, C3) versus francolite are present in roughly equal proportions. Francolite often tends to form crusts or rinds of fibrously radiating crystals around quartz grains, pellets and other material (Plates 7A, 7B, 7C). Rapson-McGugan (1970) considers these phosphate cements to be primary in nature with the "fluorapatite" variety (francolite-type C6, the present study) to be a recrystallized version of the collodial form (i.e. C1, C2, C3 type, the present study). The microprobe chemical analysis work done in the present study tends to support this view in that chemically, the two varieties are indistinguishable.[56] The phosphate pebbles (I2) are of two basic types: 1) a former spicule rich chert now completely phosphatized to francolite, with hematite laths often replacing central canal region of the spicules (Plate 7D); and 2) pebbles composed of C1, C2 and C3 primary cements containing very few spicules, or clastic debris. Most of the pellets in the RCBP are organic rich, structureless and nearly isotropic under crossed polars. Ooids are often recrystalized to francolite. Pellets in the RCBP show a platelet-like, layered structure under the scanning electron microscope (Plates

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[56] Though minor differences are present

7E, 7F).

Diagenetic processes in the RCBP seem to have followed the following order: early phosphate replacement of sponge spicules and spicular cherts, some recrystallization of early phosphate to francolite cement, replacement of phosphate cements by calcite and to a lesser degree dolomites and finally silicification filling in open pores, with some chert replacing phosphate cements. Fluorite is also replacing spicule remains, and was probably contemporaneous with the phosphate replacement.

Ranger Canyon (RCUP) and Mowitch Formation (MBP)

The Ranger Canyon Upper phosphate zone (RCUP) and Mowitch Formation Basal Phosphate (MBP) is marked by nodules, reworked phosphate pebbles, structureless pellets, bones and several types of primary cement (C1, C2, C3 and C6). These two zones are very similar petrographically to the RCBP and only major differences will be discussed. "Host" rocks for the phosphate are either conglomerates or fine grained sandstones. Conglomerate clast sizes tend to be smaller (<10 cm) than in the RCBP, although clasts up to 50 cm were observed. C1 type and francolite cements tend to bind these conglomerates, and show a similar matrix of pitted quartz, chert, and phosphatized sponge spicules. Sandstone host rocks show the same petrographic features as in the RCBP, with more intense silicification of the entire rock being evident. Replacement features are nearly identical to those described in the RCBP with some evidence, in these two zones, of dolomite replacing chert. Anhydrite, chert and calcite have replaced phosphatic bones and pellets. Phosphate was also replacing detrital quartz in some of the sandstone of the MBP.

Mowitch Formation (MUP

The Mowitch Formation Upper phosphate (MUP) consists of phosphate pebbles (I2), pellets, bones and shells in a fine to very fine grained, poorly sorted, angular calcite/clay cemented, sandstone. These pebbles are up to 3 cm long and are composed of francolite and/or C2 type cements, cementing fine grained quartz sand grains. Some reworked pebbles appear to be compositionally identical to insitu phosphatic sandstones discussed in the RCBP section. These pebbles are in a matrix of clastic quartz, pellets, bones, phosphatic shells, and detrital hematite. Other pebbles appear to be aggregates of structureless pellets or phosphatized sponge spicule (formerly cherts?). Replacement features include pellets and spicules being replaced by francolite type cement, and calcite replacing original clay cement. The MUP zone is likely a secondary reworked phosphate occurrence.

Spray River Group

The Spray River Group phosphorites are characterized mineralogically as having a high degree of CO_3^{-2} substitution i.e. approaching the francolite end member (Table 28). Dahllite is present as bone remains in some samples (Plate 8C).

Phosphates within the Spray River Group are best developed in the Whistler Member of the Sulphur Mountain Formation. Petrographic examination of a dozen samples from the Whistler phosphorites shows a predominance of the nucleated and oolitic (lithotypes P1, P2 - Table 2, Plates 8D, 8E) pellets, and phosphatized *Lingulid(?)* shell fragments (Plates 8A, 8B). Structureless pellets, bones, intraclasts, and C3 type cements occur less frequently (Plate 8F). The phosphates usually are hosted by a non-burrowed, very finely crystalline, well laminated silty dolomite or less commonly a dolomitic siltstone. Phosphate pellets are usually subrounded, moderately to well sorted, loosely packed, 0.10 to 0.40 mm in size and are often cored with detrital quartz, zircons, dolomite, or shell fragments. Detrital hematite, microcline, muscovite all occur as minor minerals.

Fernie Group

The mineralogical characteristics of Jurassic age phosphates are different than those of the other geological periods discussed, based on their chemical characteristics. Lower Jurassic phosphates more closely approach fluorapatite with respect to their CaO/P_2O_5 ratios, CO_3 and Na_2O contents (Table 28). This same group more closely approaches francolite with respect to their F/P_2O_5 ratio, CaO, P_2O_5, F and MgO contents. Thus the Lower Jurassic phosphates would seem to overall more closely approach a carbonate poor francolite. The Middle Jurassic phosphates more closely resemble fluorapatite with respect to their CaO/P_2O_5 ratios, CO_2 (though just), F and Na_2O. Conversely, this same group more closely approximates francolite with regards to their F/P_2O_5 ratio, CaO, P_2O_5 and MgO contents. The high CO_2 content in the Middle Jurassic phosphates would tend to make them slightly more "francolitic" in mineralogy than the Lower Jurassic forms. [57]

Basal Fernie phosphate zone

The basal fernie phosphate (BFP) zone is characterized by three main modes of occurrences: pelletal phosphorites, coarse clastics hosting phosphates (conglomerates and sandstones) and phosphatic shales.

The pelletal phosphorites are the most economically important and consist overwhelmingly of the structureless pelletal (P3) petrographic lithotype (Plate 9A). The nucleated (P2) and oolitic (P1) varieties are generally present in less than 20% abundance, although in the north-central deposits (Fig. 20, Areas II and III) the abundance rise to nearly 35% in some cases. Nodules, intraclasts, and phosphatic bone material make up the remainder of the phosphate material in these pelletal phosphorites. Structureless pellets in the pelletal phosphorites tend to have the following characteristics: sizes ranging from 0.05 to 0.50 mm - with a mean value of about 0.13 mm, most are well to moderately well sorted, subrounded to rounded, moderately well sorted, and most are very loosely packed. More densely packed varieties are found in Area I, Fernie Basin (Fig. 20), particularily in the south, where pellets are very densely packed with some pellets showing plastic-like boundary adjustments (Plate 9A). Lowell (1952) has suggested that this feature suggests early compaction of pellets while in a gel-like or plastic state. Pellets appear bleached, due to weathering, at some localities but most are not. Scanning electron microscope micrographs show these pellets to be composed of very thin (50-100 nanometers?) platelets of fluorapatite (Plate 9B). Other pellets show an anhedral, very finely crystalline, fluorapatite structure (Plates 9C, 9D). Cook (1972) describes similar fluorapatite hexagonal crystallites from the Duchess Deposit in

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[57] It is hoped the reader can appreciate the problem in classifying these mineral species, when they so closely fall between the two end members.

Queensland, Australia. Most pelletal phosphorites from the present study have a quartz silt matrix, and a carbonate, usually recrystallized sparry calcite-cement. Pelletal phosphates from Areas II and III (Fig. 20) tend to have more calcite cement and more silty matrix than those in Area 1. These impurities are reflected in an overall lower grade of phosphorites (8-15% P_2O_5 generally) in these areas (i.e. Areas II and III) as compared to the Fernie Basin region (Area I). Dolomite, clay and barite cements are occasionally found in these pelletal phosphorites but are not common. Distributions of phosphorous within the pellets, silica as quartz within the matrix and occasionally within the pellets, and rare barium as barite cement was confirmed by X-ray mapping techniques utilizing the scanning electron microscope (Plate 11). Nucleated pellets far outnumbered true oolitic pellets and are generally cored with a clastic quartz grain. Many of these nucleated pellets are really clastic quartz with a thin rim of C1 to C3 cements. Mineral replacement within these pelletal phosphorites is dominated by calcite replacement (Plate 9E). Calcite is seen to replace phosphate pellets, quartz grains and occasionally feldspar grains. Calcite replacement of phosphate accounts for much of the lowering of grade at some locations. The pellets themselves show very little evidence of having been anything else other than phosphate. Although they are generally organic rich, they rarely contain any micro or other fossil remains which might suggest a faecal origin. Likewise, little evidence is present to suggest that the pellets may have been calcium carbonate at one time, and were subsequently phosphatized. Most of the BFP pellets likely formed autheginically from phosphorous rich interstitial waters in muds below the water / mud interface.

The Basal Fernie phosphate zone is in many places represented by a thin (<30 cm) phosphate-bearing sandstone or conglomerate, that occupies the eastern shelf facies area (Fig. 37). The petrographic nature of this basal clastic unit (BFP) is apparently very dependent upon the subcropping formation. In the Crowsnest Pass area, subcropped by the very clean Tunnel Mountain sandstones, the BFP sandstone is well sorted, well rounded, medium grained, quartzose sandstone that contains mostly structureless pellets (P3), intraclasts (I1), nodules or pebbles and some bone remains. Structureless pellets predominated over the other phosphate lithotypes and generally occupy less than 10% of the rock by volume (Plate 9F). In the Livingstone Range, where the subcropping formation is the subangular siltstones of the Sulphur Mountain Formation, the phosphate consists of structureless pellets and intraclasts in a poorly sorted, subangular to rounded, very fine grained sandstone (Plate 10A). This relationship of subcropping formation to BFP seem to hold true northward, where the Whitehorse Formation subcrops, dolomite intraclasts are often present in the BFP sandstone zone. In the Jasper region and northward, westernmost BFP sections often show phosphate intraclasts and pebble rich conglomerates (Plate 10B). Intraclasts and some phosphate pebbles are generally rich in silt size clastic quartz and dolomite material. Phosphate cements are generally not present in the BFP however some of the phosphate pebbles within these conglomerates show evidence of previous cementation by phosphates. One such pebble contained abundant pelecypod remains and smaller phosphate intraclasts. One such intraclast, within the pebble, contains a francolite cemented fine grained sandstone, very similar petrographically to some of the RCBP zone. Several episodes of phosphate precipitation, erosion and transportation are therefore indicated. All of the phosphate found within these sandstones and conglomerates appears to be reworked and transported material.

Phosphatic shales are the third most common expression of the BFP, and in this case the source of phosphatic material is often very difficult to discern. This is due to the very fine grained nature of the material and is further masked by high organic contents. The most common phosphate petrographic lithotype is the elongated pellets, typically set in a very argillaceous well laminated, unburrowed calcareous shale (Plate 10C). These pellets tend to have many of the characteristics of the pelletal phosphorites however some pronounced differences are present. The elongate pellets are sometimes smaller in size (mean value approximately 0.07-0.10 mm), are not well sorted and have a typically elongated to lensoidal shape. These pellets appear to be precursors to the "true" pellets, and perhaps formed as a phosphatic gel in this argillaceous setting as suggested by Lowe (1952).

Nordegg Member Phosphate

Phosphate within the Nordegg Member is found within the NMLSP, the NMP, and FOP horizons (Fig. 19). The petrographic characteristics of these phosphates were not investigated in detail as phosphate contents are generally less than 5% P_2O_5 and of little economic interest.

The Nordegg Member lower shale phosphate (NMLSP) is a series of organic rich[51] shales and argillaceous limestones that contain up to 4% P_2O_5 (most in the 1 to 2% P_2O_5 range), generally in the form of phosphatic bone or shell debris. This fossil material is frequently replaced by sparry calcite, some fossils having been completely replaced by calcite.

Phosphate in the Nordegg Member phosphate (NMP) zone is best developed in chertified sandstone sequences within the Nordegg Member. The phosphate occurs as structureless and nucleated pellets, in part, being replaced by chert or calcite. Both varieties seem to be present in roughly equal abundance, throughout the NMP. Most of the nucleated variety have quartz cores, a thin pyrite layer and the enveloping phosphate. Phosphate nodules are also present in these sandstones, though not abundantly so. Chertification has been extensive in the Nordegg Member, masking many of the primary lithologies, and may have chertified many of the primary phosphate petrographic textures.

The Fernie Oxytoma phosphate (FOP) zone consists mainly of phosphate pebbles in a conglomerate, structureless pellets in a well sorted, quartzose sandstone, or as phosphatized fossil shell debris. The base of the *Oxytoma* horizon at section 123 is also marked by a phosphate pebble conglomerate, though this horizon was not seen anywhere else. The FOP phosphates are all reworked material.

The Rock Creek Member phosphatic zones consist primarily of phosphate nodules and more rarely structureless, nucleated and oolitic pellets. Nodules are by far the most common lithotype, and obtain sizes of up to 8 to 10 cm. The nodules are diagenetic showing clear evidence of having grown in place. The internal structures of most nodules appear identical to the surrounding groundmass, except for the extensive phosphatization (Plate 10D). These nodules are frequently found in an iron rich - often siderite or pyrite - fine grained, carbonate rich, moderately well sorted, sub-angular to sub rounded, sandstone. Belemnites, ammonites and pelecypods abound within these nodule zones and some of these fossils appear to have been phosphatized (Plate 10E). Glauconite is sometimes present as a minor mineral. The phosphatic material within the nodules is a mixture of C1, C2 and C3 type cements and recrystallized fibrous "francolite" type cement. Nodules often have phosphatized shell remains within them that may have acted as nucleation sites for diagenetic phosphate precipitation. The pelletal phosphorites often consist of phosphatized forams, bryozoans(?), algae, and small pelecypod remains. Several layers of phosphate have apparently been added to many pellets giving them an oolitic texture (Plate 10F). Pyrite is often seen at the cores of pellets as fine laminae within non-fossil type pellets. Calcite replacement has affected many of the pelletal varieties, and some sections show only calcified "ghosts" of what was very likely a phosphate pellet. The Rock Creek Member phosphates are therefore seen as resulting from early diagenetic phosphatization of fossil material and the formation of diagenetic nodules.

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[51] Organic content of a single sample from the NMLSP, performed by T.G. Powell and L.R. Snowdon at the Geological Survey of Canada, Calgary office revealed 13.36% Total carbon, 12.17% Total Organic Carbon and having a potential oil yield of 3.06 kg/tonne.

C. Depositional Models

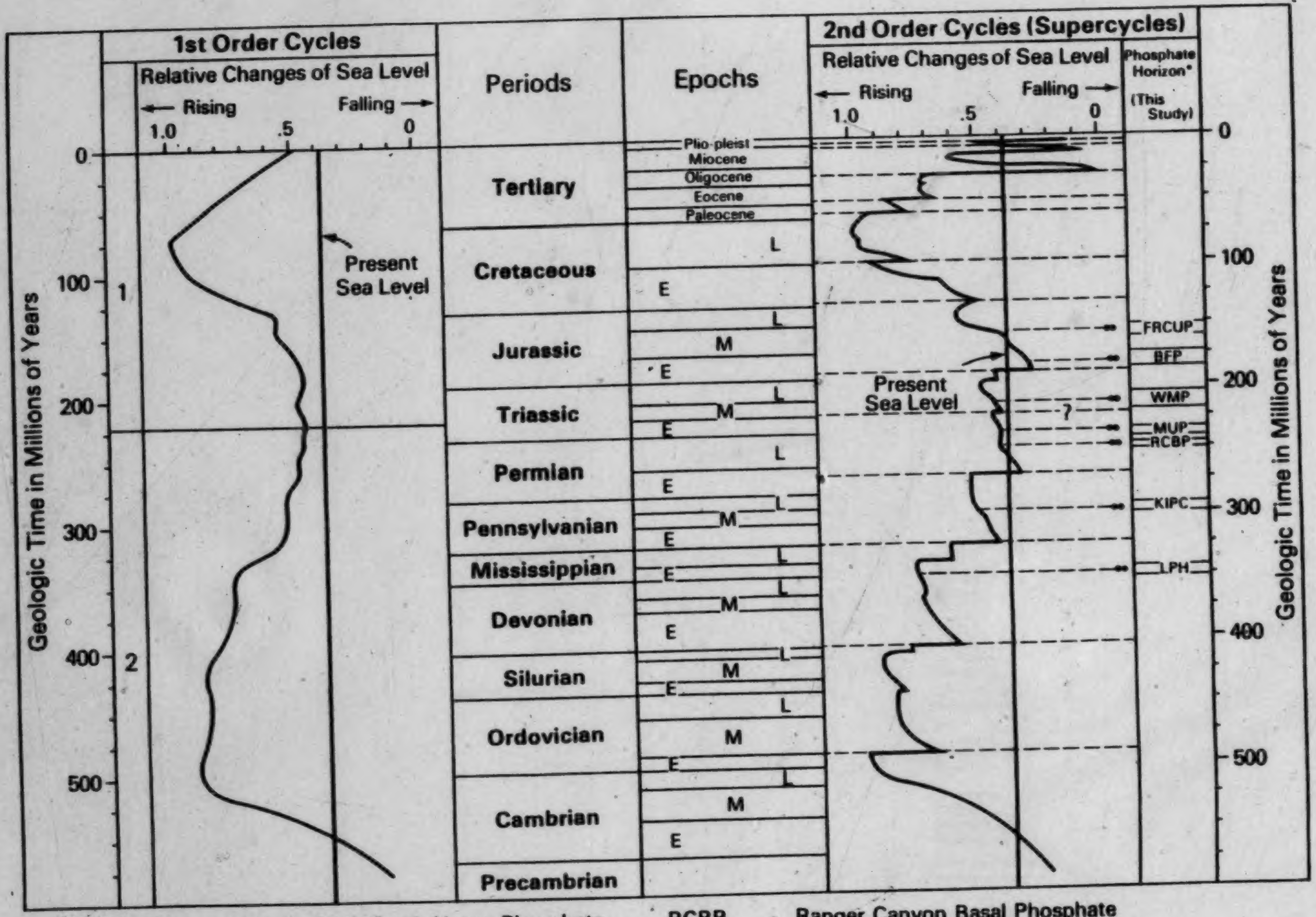
Exshaw Formation

The Exshaw Formation represents a widespread black shale unit, genetically though not time correlative, with many similar units throughout North America. The North American tectonic setting, in early to middle Devonian time, was one of transcurrent movement in the Applachian area resulting in the onset of the Acadian Orogeny (Morel and Irving, 1978). By middle to late Devonian time this transcurrent movement had developed into a spreading center and "Atlantic Two" (Morel and Irving, 1978) was born (Fig. 32). This was accompanied by a worldwide rise in sea level (Vail et al., 1977, Fig. 31). This transgressive event is one of Vail's et al. (1977) second order cycles and resulted in a gradual flooding of the North American continent (Laurasia) in a south to north fashion. Thus the Marcellus Shale in New York is Middle Devonian in age, while the Exshaw

Formation in this study area is Upper Devonian to Early Mississippian in age, both are genetically related however. On the west coast of Laurasia another spreading center, west of the present day Vancouver Island, was periodically active producing subduction, obduction, and Island Arc features in the interior and eastern parts of British Columbia. A volcanic island arc chain, corresponding to the Omineca Geanticline, developed just west of the Alberta Trough (Fig. 32). This suggestion is supported by the presence of two bentonite horizons described within the Exshaw in the study area. It also appears likely that Montania and the Peace River Arch were mildly positive features, though possibly not subaerially exposed (McCrossan and Glaister, 1964). Strongly negative, basinal areas at this time included parts of northeastern British Columbia, the Alberta Trough, as evidenced by thickening of several westernmost Exshaw sections in this study (Fig. 27) and an area in the Butte, Montana region. Macqueen and Sandberg (1970) also describe a fork like depositional trough system throughout southern Alberta and extending into northern Montana (Fig. 32).

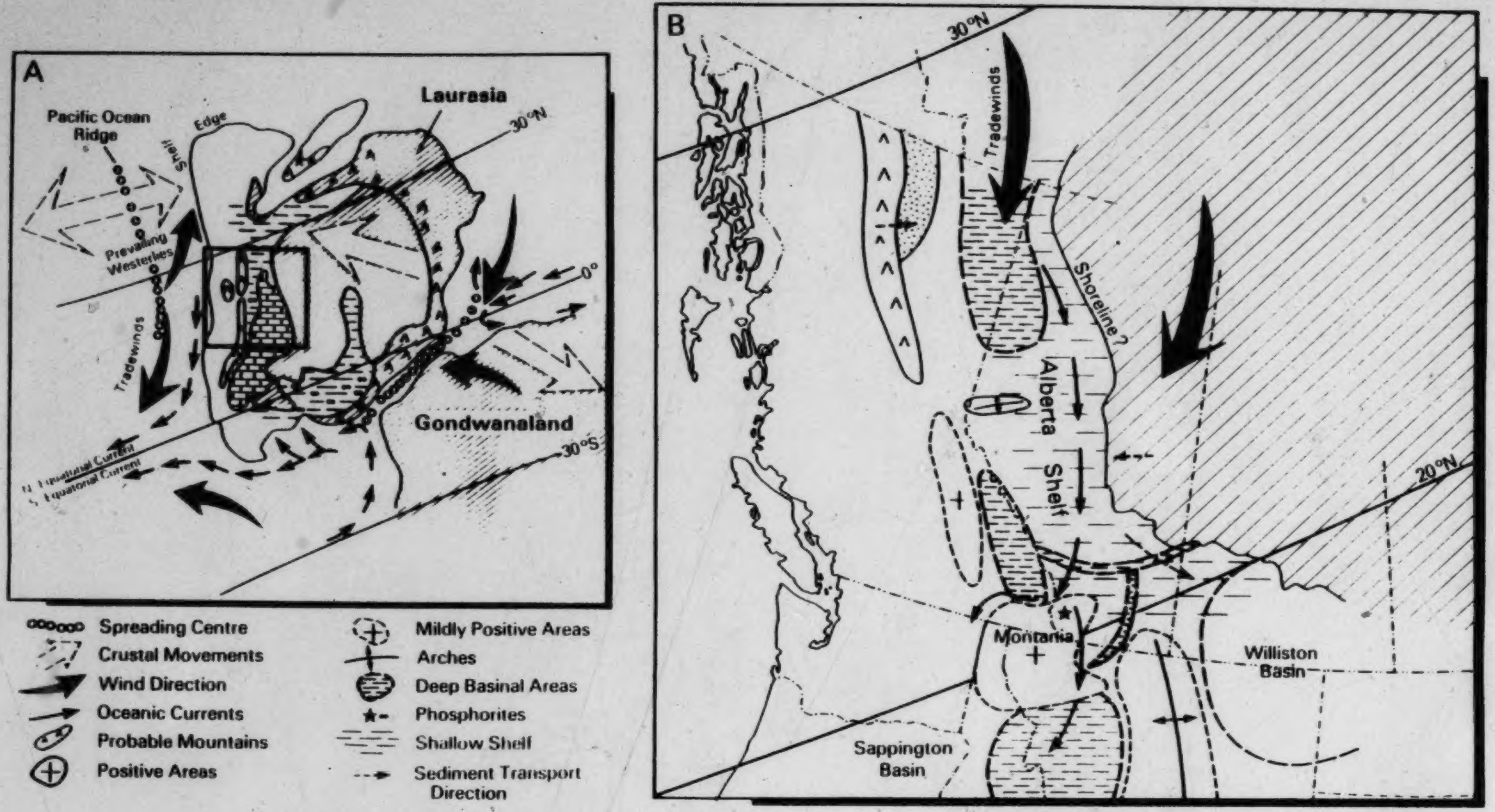
The paleogeographic setting in this area was reconstructed based on the aforementioned tectonic elements, the works by Ettensohn and Barron (1981) and Irving (1979) - Figures 32a and 32b. This study area lay at about 20° to 24° N latitude and was influenced by the Trade Winds. The Trade Wind belt likely produced southward flowing oceanic currents along the paleoshoreline, and the prevailing wind direction blew parallel or slightly obliquely off the coast line. Having set the stage, an attempt will now be made to explain the Exshaw Formation phosphorites.

After the Palliser Wabamun carbonates were deposited in Famennian time, there is some facies evidence to support a minor, short regression of the sea in late Famennian time (McCrossan and Glaister, 1964). This is supported by this study's findings of possible paleosols and abundant hematite in the BSM. The Exshaw everywhere sharply overlies the Palliser, and the BSM is found throughout a very large part of the study area. These two characteristics are common to many of the other North American genetic equivalent "black shale" units. The presence of a thin (millimetres to one metre) phosphatic, bone, pebble sandstone at the base of this cycle - regardless of the time - is very widespread (Ettensohn and Barron, 1981). This sandstone (BSM and others) likely represents a thin transgressive sandstone, being the only evidence of a possible Late Famennian regressive



*FRCUP - Fernie Rock Creek Upper Phosphate
BFP - Basal Fernie Phosphate
WMP - Whistler Member Phosphate
MUP - Mowitch Upper Phosphate
RCBP - Ranger Canyon Basal Phosphate
KIPC - Kananaskis Interformational Phosphate Conglomerate
LPH - Lower Phosphate Horizon - Exshaw Formation

Figure 31. First and second order global cycles of relative sea level during Phanerozoic time and phosphate zones in Alberta and British Columbia (modified from Vail et. al, 1977).


A
Laurasia
Pacific Ocean Ridge
Shelf Edge
30°N
Prevailing Westerlies
Tradewinds
0°
Gondwanaland
N. Equatorial Current
S. Equatorial Current
30°S
Spreading Centre
Crustal Movements
Wind Direction
Oceanic Currents
Probable Mountains
Positive Areas
Mildly Positive Areas
Arches
Deep Basinal Areas
Phosphorites
Shallow Shelf
Sediment Transport Direction
B
30°N
Tradewinds
Shoreline?
Alberta
Shelf
20°N
Montania
Williston Basin
Sappington Basin

Paleogeography After; McCrossan and Glaister, 1964, Douglas, 1970, McQueen and Sandberg, 1970, and Ettensohn and Baron, 1981.

Figure 32. Paleogeographic setting of North America and western Canada, Late Devonian to Early Mississippian time

sequence (Fig 3). It is not certain whether the phosphatic material in the BSM was formed during the brief regressive phase or the ensuing transgressive event. The latter is favoured by this author as the almost now compulsory "upwelling" of deeper ocean layers to form phosphorites would be of little use in a retreating, regressive sea. Sheldon (1980) has put forth a theory that suggests many phosphate deposits seem to have formed at the onset of episodes of sea water vertical mixing (high sea level stands) after long periods of stability and low sea level stand. Low sea level stands allow phosphorous to build up in the deep ocean sinks. This was probably the case for the BSM phosphorites, having formed during the rapid transgressive phase that marks the beginning of deposition of the Exshaw Formation. A rapid transgressive phase and a rapid return to quiet, and likely stagnant, euxinic conditions is suggested by the basal bentonite bed immediately overlying the BSM in many locations. The Exshaw Formation is highly organic rich and most authors agree that due to this high organic content, the thinly evenly bedded nature, abundant pyrite, and the paucity of fossils, that stagnant, euxinic, reducing conditions must have existed. How these conditions came to be and the water depth at the time of deposition is of some debate. McQueen and Sandberg (1970) suggest a series of extremely shallow, stagnant marine or brackish lagoons, formed by gentle downwarping in the previously shallow Palliser sea. Ettensohn and Barron (1981) suggest that the initial black shale sediments may have been shallow, however as the transgression proceeded water depth would steadily have increased. These same authors suggest at the very least a 230 m water depth for related black shales in eastern Kentucky. From isopach maps prepared for this study there is some suggestion of a series of northeast trending sills that may lend support to the "shallow water lagoon" theory (Fig. 28). If the Exshaw sediments that were deposited on the multiply warped Alberta Arch (Fig. 2) were in shallow lagoons, those sections farther west - in the Alberta Trough - most certainly were deposited in very deep water (Fig. 28). Shallow water conditions are definitely indicated in the Crowsnest Pass and southeastern British Columbia regions.[59] At section 226 (Fig. 27) a highly restricted (in terms of geographical areal extent) sponge spicule accumulation, equivalent to algae-sponge unit of the Sappington Formation, directly overlies a phosphatic shaly equivalent of the BSM. The

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[59] Thick carbonates overly the Palliser Formation in southeastern British Columbia and are likely related to the Sappington Formation. They may have developed on or around the slightly positive Montania.

Middle Phosphate zone overlies this, though not directly, and together they suggest an area of upwelling oceanic water, probably at shallow depths. This is supported by the paleogeographic map (Fig. 32) that shows southward currents flowing parallel to the coastline, impinging on the slightly positive Montania and/or Cambridge Arch, being diverted westward or southward over Montania. Either of these conditions are known to produce upwelling. If diverted to the west, seaward past the Alberta Trough divergent type upwelling would have occured, overturning water in the Alberta Trough. If the currents were diverted southward over the mildly positive Montania, dynamic upwelling would have occurred. In either case the result should be the same: a continued supply of PO_4^- for living organisms to thrive on (e.g. sponges). This then is the first important step in the formation of phosphates as was discussed previously. Petrographic evidence shows the phosphates from north of the Crowsnest Pass to be elongated pellets with an argillaceous matrix, suggesting they formed diagenetically within near surface muds. Interstitial waters would become highly concentrated with PO_4^- due to the continual rain and degradation of organic material to the bottom brought on by the upwelling process. South of the Crowsnest Pass, the pellets are more of the nucleated and pelletal varieties, and are matrix free - suggesting shallower water, and possible formation above the sediment/water interface by intermittent suspension. Sweet and Crowder (1982) in a study of Cambrian phosphorites from Spitsbergen recognized oolitic and nucleated pellet types, many with francolite type layering, and concluded a primary origin by rolling action in a shallow water tidal environment. Swirydczuk et al (1981) describe oolitic phosphorites from a near shore, sandstone hosted, Pliocene lacustrine environment. These authors conclude that the oolites formed first as carbonates in an active wave environment, and were later phosphatized during a regional transgression. The Swirydczuk et al. example is less similar in overall setting to the Exshaw oolites and therefore the Sweet and Crowder (1982) interpretation is favored in explaining the Exshaw phosphorites. Nucleated and oolitic pelletal phosphates south of Crowsnest Pass also tend to support the idea of a mildly positive Montania in this area. The phosphate beds are not thick anywhere in the Exshaw and as the transgression continued and the waters continued to deepen, the upwelling processes likely became less efficient, and phosphate precipitation ceased. Toward the end of deposition of the LCBS Member another volcanic eruption to the west

(?) deposited the Upper Bentonite bed (UBB). The LCBS member becomes progressively more silty and calcareous above the UBB and grades upward gradationally into the Upper Limestone Member. McQueen and Sandberg (1970) suggest a regressive marginal-marine environment of widespread, well-oxygenated tidal flats, under the influence of normal waves and currents for the Upper Limestone Member. An isopach map of this member shows it to be thickest along an northeast trending trough (Fig. 29). It is apparent that during LCBS Member time this was a mildly positive area that caused a slight thinning of the overlying LCBS Member. During or prior to the Upper Limestone Member time, the sill apparently collapsed and became an axis for deposition of the ULM. It is difficult to imagine an area of tidal flats stretching over 500 kms by 200 kms. While burrows, and other evidence cited by McQueen and Sandberg (1970) likely indicate a tidal flat environment, an alternative suggestion might be a very fine grained delta or pro-delta complex similar to that attributed to the dolomitic siltstones of the Triassic-Sulphur Mountain Formation (Gibson, 1974). Very fine grain size, flow rolls and other features seen in the ULM are also seen in the Sulphur Mountain Formation. The isopach map of the ULM (Fig. 29) suggests a lobate morphology, perhaps a result of deposition from a single point source, i.e. a delta. The Upper Phosphate horizon (UPH) that caps the ULM in two localities marks the end of the minor ULM regressive phase, within the larger second order cycle Devonian to late Mississippian transgressive event (Fig. 31). The UPH is a mixture of reworked phosphate material and may be a transgressive lag deposit. The original phosphate may have been precipitated much farther west and been transported eastward during the transgressive phase. Alternatively the UPH may have been deposited in a tidal flat environment, similar to that described by Birch (1980) for Miocene phosphates on the coast of South Africa.

Spray Lakes / Ishbel Groups

The Pennsylvanian Spray Lakes Group phosphates are fairly insignificant economically. They are thought to have formed in a manner similar to the Permian, Ishbel Group ones, and so only the Permian phosphates will be dealt with in detail.

The close of the Mississippian period saw a global drop in sea levels (Fig. 31) which was likely a reflection of the collision of Gondwana and Laurasia, closing "Atlantic II"

(Morel and Irving, 1978). Throughout the Pennsylvanian the relative sea level rose until the middle of the early Permian, when a sudden lowering of sea levels took place. Sea levels flucuated at around the present day level throughout the Permian, and only began to rise significantly during the Traissic. Continental plate movement was thought to be fairly minimal all through the Permo-Pennsylvanian (Morel and Irving, 1978). In the Alberta Trough/Arch areas the history of sea level rise and fall was more complex.

Climatic conditions throughout the Permo-Pennsylvanian in this area are thought to have been hot and dry, as evidenced by an inferred low paleo-latitude, and aeolian dune, evaporite and redbed sequences in the Western U.S.A. Clastic sedimentation was also thought to be very minimal off of low lying continental areas. The paleographic setting from the present study area and south into northern Utah, were ideal for coastal upwelling brought on by Trade Winds blowing parallel to the paleocoastline (Fig. 33) during the Permian (Guadalupian). Upwelling is even more likely to occur if, as has been well documented in the western U.S. Phosphoria Formation (Sheldon, et al., 1967), coastal currents, encounter an east-west barrier and are diverted seaward (Fig. 33) producing divergent upwelling. This seems like it may have been possible in the southern parts of the Alberta Trough and Arch. If Montania was a positive feature, currents may have been diverted seaward (west) or up and over Montania producing dynamic upwelling. Whether Montania was a land area or mildly positive area can only be speculated upon, as no Permian rocks have been preserved in this area. However, given the known land positions in Alberta and southwest Montana, it is more reasonable to assume an intervening land area, than an oceanic one.

The history of Permo-Pennsylvanian and associated phosphate sedimentation in the study area would appear to be as follows. Toward the end of Kananaskis Formation deposition (Atokan) sea levels began to drop, leaving much of the shelf areas (Alberta Arch) subaerially exposed in a series of supratidal sabkha environments. Rapson (1962) postulates a series of restricted to evaporitic coastal lagoonal environments in which silica and carbonate were precipitated, compacted and contracted through burial and evaporation, fractured and brecciated, and then re-cemented with silica.[60] These sharp stones and chert breccias that were formed were then likely reworked somewhat as the

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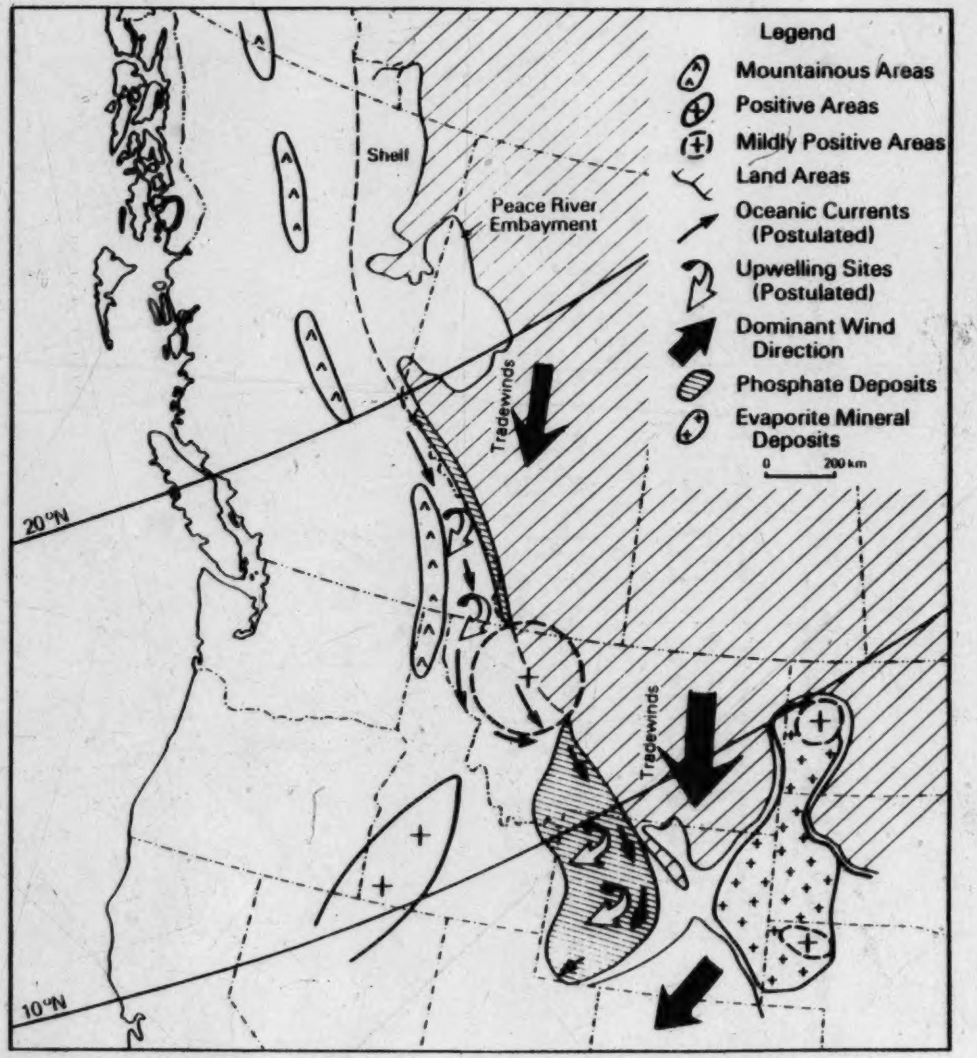
[60] The reader is referred to Rapson (1962) for more geochemical details of this process.


Legend
Mountainous Areas
Positive Areas
Mildly Positive Areas
Land Areas
Oceanic Currents (Postulated)
Upwelling Sites (Postulated)
Dominant Wind Direction
Phosphate Deposits
Evaporite Mineral Deposits
0
200 km
Shelf
Peace River Embayment
Tradewinds
Tradewinds
20°N
10°N

Paleogeographic Reconstruction After; McCrossan and Glaister, 1964, Douglas, 1970, Irving, 1978, and Sheldon, 1964

Figure 33. Paleogeographic reconstruction of the Permian (Guadalupian) in western Canada and Western United States seas continued to retreat. Primary silica cementation seems to have cemented these breccio-conglomerates, known in this study as the KIP. The KIP, in some areas, is cemented with phosphate, which was probably deposited as a primary or replacement cement during the next major sea level rise, in mid Wolfcampian time. The Alberta Shelf (Arch) was probably subaerially exposed and subjected to a long period of erosion prior to this early Permian transgression. Some primary, well bedded, microsphorite type phosphate may have precipitated in intertidal areas, and then ripped up and incorporated into the KIP as phosphate pebbles. The KIP is known to have a minor component of such pebbles.

The early Permian transgression (Fig. 31) saw the progradation and deposition of eastern derived clastics onto the shelf, into the Alberta Trough and possibly along the eastern flanks of the western belt island shown on Figure 33.[61] The presence of this western Island would likely preclude any very deep water sedimentary environments, and shelf marginal to shelf deposits were probably more common.

Johnston Canyon Phosphate Model

The Johnston Canyon Formation is the earliest Permian strata known, and consists largely of dark interbedded shales, siltstones, cherts and some phosphorites. This assemblage would suggest a fairly deep outer shelf to shelf margin depositional environment and is supported by the following lines of evidence:

1. Abundant *Zoophycus* trace fossils which most ichnologists put into the *Zoophycos* Ichnofacies assemblage, a depositional environment in the slope to basin transition area (Howard, 1978; Chamberlain, 1978). [62]Aside from *Zoophycus* traces, very few other trace fossils were observed or have been reported, again supporting a deeper water environment, slope to basin position.
2. Organic rich shales, cherts and fine grained siltstone lithologies, suggesting deeper, poorly oxygenated waters.
3. Phosphate pebble zones (JCIP) that show basal scour and some suggestion of

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[61] The Telford and Ross Creek Formations consist largely of carbonates likely developed along this island (McCrosan and Glaister, 1964).

[62] Strictly speaking, the presence of a single trace fossil is not enough to place it into anyone ichnofacies, a complete or large number of members from the assemblage is required to be certain.

upward grading - perhaps indicating a turbidite origin from a more shelf position.

4. Abundant phosphate nodules in the JCIP zone, suggest from modern analogies, a fairly deep water environment. Most modern phosphate nodules are found at the edge of the continental shelf or the upper slope region (Bentor, 1980).
5. Pelletal phosphate horizons reported (Cominco Ltd, J. Hamilton, pers. comm.) - though not seen by this author - would probably have formed in an outer shelf area as this is the environmental interpretation given to the Permian Phosphoria pelletal phosphorites (Sheldon et al., 1967).

The Telford and Ross Creek Formations all lie conformably upon each other where they crop out in southeastern British Columbia. However in Alberta, and the extreme eastern parts of southeastern British Columbia, these two formations are not generally present, probably due to the middle Guadalupian erosional event.

Ranger Canyon Phosphate Model

In the Lower Guadalupian the ocean gradually retreated and produced a long period of widespread regional erosion, now marked by the RCBP zone. Erosion removed Guadalupian to Pennsylvanian age strata and was probably accompanied by uplift and tilting as shown by an angular unconformity between the Johnston Canyon and Ranger Canyon Formations in southwestern British Columbia (McGugan and Rapson, 1962). The RCBP zone, is, over most of the study area, represented by a poorly sorted, matrix to clast supported, phosphate cemented chert pebble to boulder conglomerate (Fig. 34). Within the RCBP a number of other sub-facies occur, the second most common being the fine grained, well sorted phosphate cemented sandstone. The fine grained sandstone facies commonly directly overlies or grades laterally into very fine grained dolomites. The dolomite facies often contains patchy areas of phosphate cement or scattered nodules, and at section 21 was observed to show wavey laminations, some "birdseye" textures and was heavily silicified. A fourth facies comprised of reworked phosphate pebbles is found in the central and northern regions. The petrographic lithotypes of these pebbles are either of the completely phosphatized sponge spicule chert variety or the former microsphorite variety. The latter lithology would suggest an area somewhere to the

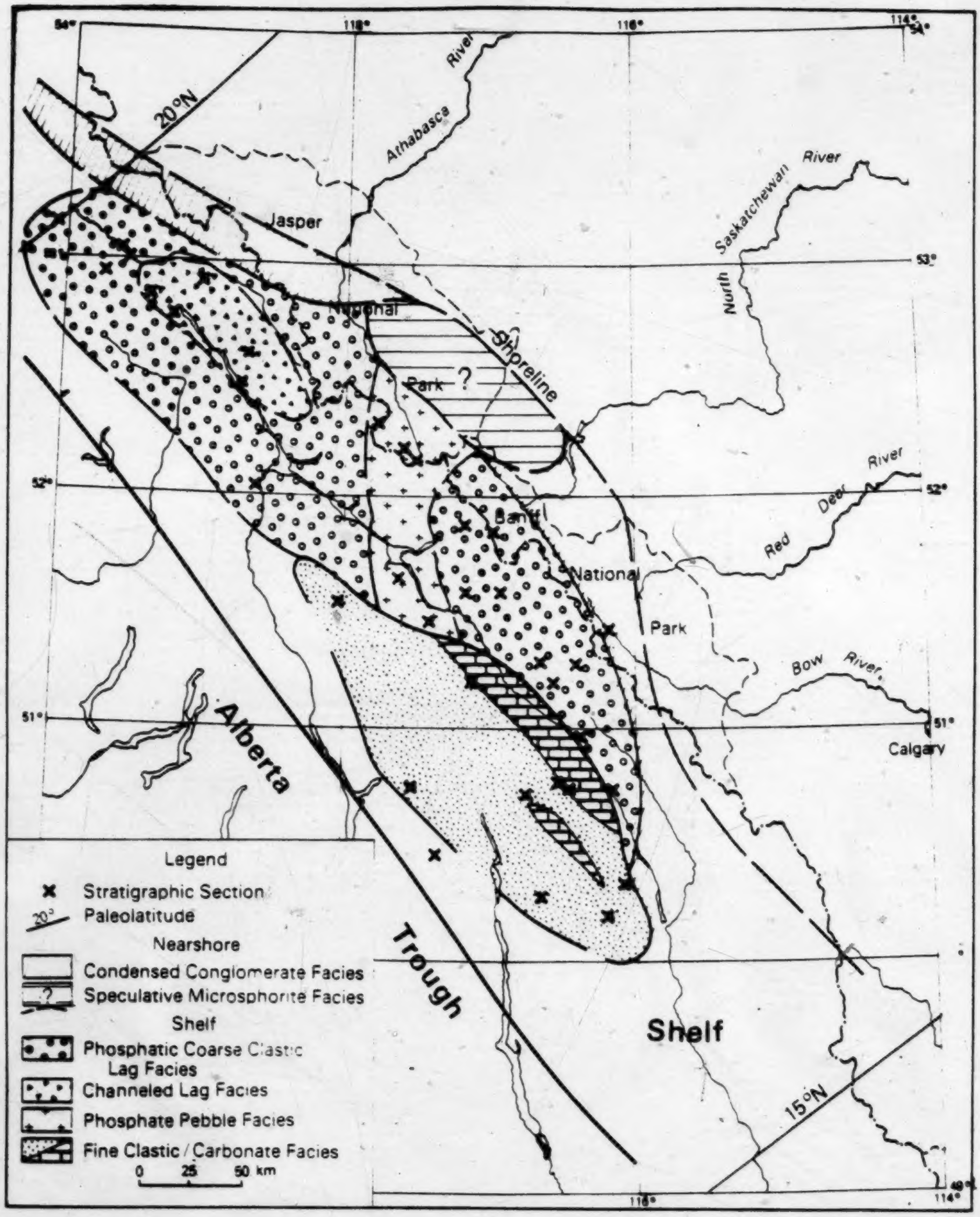
54°
118°
116°
114°
54°
20°N
Athabasca River
Jasper
National
Park
?
Shoreline
North Saskatchewan River
53°
52°
Banff
National
Park
Red Deer River
52°
Bow River
51°
51°
Calgary
Alberta
Trough
Shelf
15°N
116°
114°
49°
Legend
Stratigraphic Section
Paleolatitude
Nearshore
Condensed Conglomerate Facies
Speculative Microsphorite Facies
Shelf
Phosphatic Coarse Clastic Lag Facies
Channeled Lag Facies
Phosphate Pebble Facies
Fine Clastic / Carbonate Facies
0
25
50 km

Figure 34. Ranger Canyon Basal Phosphate Horizon — Lithofacies map — Palinspastically restored

east (Fig. 34) of primary microsphorite deposition. Sponge spicule accumulations need not accumulate only in deeper waters and Rapson-McGugan (1970) suggests a near shore to intertidal region of accumulation for many of the Ranger Canyon sponge spicules. Cressman and Swanson (1964) suggest that the Permian sponge spicules in the western U.S. Phosphoria Formation are of the *Demospongia* class and are thought to thrive in water depths less than 50 metres (i.e. photic zone), in normal marine salinity, moderate current velocities (2-3 km/hr) and live on nearly any substrate except fine sand. Birch (1980) describes microsphorite precipitated directly from the water column in southern Africa associated with: prolific growth of siliceous phytoplankton, adjacent to a hot dry desert, intense surface upwellings and formed in a restricted lagoon or estuarine environment. The foregoing would seem to provide a reasonable analogue for the original depositional environment of the reworked phosphate pebbles. The microsphorite may have been deposited in a lagoonal area, very close to the land, which was perhaps drained by an estuary or tidal inlet. Periodic storms may have ripped up the microsphorite, rounded it into flat pebbles which were then transported seaward in the tidal channels. The pebbles may also have been deposited in a nearshore beach environment, however the imbrication of clasts indicates some current activity. Folk (1973) describes some very similar flat pebble conglomerates composed of radiolarian cherts, sometimes composed of phosphate, in the Caballos novaculite (Devonian) of Texas. The intrepretation Folk gives for these is as storm rip-up clasts derived from laminated sediments formed in intertidal to shallow subtidal mudflat environments. McBride and Folk (1977) suggests (at least Folk does) that these same Caballos flat pebble conglomerates were deposited in tidal channels. The combined fine sandstone/dolomitic facies may then represent reworked barrier/backbarrier environments. It should be remembered that the RCBP zone is only 3 metres thick at the very maximum and most sections are less than 1 metre. In the ensuing transgression extensive reworking and removal of much of these low stand deposits took place. What is really meant in the foregoing discussion of environments and facies distribution is "what is now left of that particular facies". Phosphate may have been deposited within the sand/dolomite facies in one or both of two ways:

1. As the Mid Guadalupian transgression advanced upwelling waters along the coastline (Fig. 33) produce prolific fluorishing and subsequent dying of life. PO_4^- would be concentrated in the bottom sediments (i.e. the sand/dolomite facies) to several hundred (?) times the normal seawater concentration. Phosphate would then precipitate authigenically between the still loose interstitial pore spaces of the sands.
2. Phosphate could also precipitate as a replacement mineral during early diagenesis. PO_4^- rich bottom waters may have percolated into the previously deposited quartz, clay or phosphate cemented sandstones and replaced the early cement with phosphate, or recrystallized existing phosphate cement.

This certainly seems possible in the dolomites, many of which show phosphate replacing dolomite, or phosphate replacing clay (?) cemented silty laminae or the formation of diagenetic nodules. This phosphatization process implies an overlying source of phosphorous that was dissolving and percolating downward to promote this phosphatization. Development of a temporary thin microsphorite, or bone/fish remain bed above the sand/dolomite facies could provide such a source. Such a source bed would then be completely dissolved, its phosphorous spent at slightly deeper levels (i.e. sand/dolomite facies) to facilitate the phosphatization processes. The etching of quartz, and cement-supported nature of the fine sandstones strongly suggest that some siliceous replacement by phosphate was going on probably in an alkaline environment (Rapson, 1970). Many of the phosphate pebbles are composed of completely phosphatized spicular cherts, which again tend to enforce the idea of an early phosphatization event. Have et al. (1982) describes phosphatized limestones and dolomites from Curacao that show very similar petrographic lithotypes to the Permian RCBP sand/dolomite facies. In the Curacao example fibrous francolite and the isotropic varieties of fluorapatite are both found filling voids and rimming calcite rhombs. Coarse grained texture was found to be critical in determining sites for phosphatization, with essentially none of the micritic limestones being phosphatized. This would also seem to hold true in this study with sandstones, silty laminae within dolomite and sponge spicule remains being preferentially phosphatized. Bushinsky (1935) describes phosphate-cemented sandstones containing sponge remains from the U.S.S.R., suggesting formation in a shallow marine basin, likely by phosphatization processes.[63]

It is quite likely that both authigenic and phosphatization processes were going on, perhaps at slightly different times. In either case the chemical environment implied by the observations and deductions made is as follows: well oxygenated shallow surface waters, normal marine salinity (sponge requirements), bottom waters that were reducing due to the abundance of organic matter and a pH around 7.0-9.0. These are not impossible geochemical environments to envisage, if organic matter were being produced at a prolific rate by upwelling and then settling to the bottom. The bottom conditions could therefore quite easily become reducing.

The RCBP zone over the rest of the study area consists of the previously described polymictite chert / dolostone, phosphate cemented, breccio-conglomerate. The origin of the conglomerates is not certain, however some possibilities may easily be eliminated. The conglomerates have many characteristics of alluvial fan deposits, however no eastern high upland area can be shown to exist at anytime during the Permian. An upland belt island to the west of the Alberta Trough has been postulated (Fig. 33), however any fan deposits off this island would have been deposited in the deep Alberta Trough and not likely reached the shelf to shelf marginal region of this study area. Likewise turbidity or similar mass flow deposits are precluded, given the historical geological context, i.e. a regressive period when the shelf was either subaerially exposed or covered with very shallow water. The trace fossil assemblage immediately below the RCBP is very sparse, but all are from the *Cruziana* ichnofacies i.e. between fair and storm weather wave base (pers. comm. G. Pemberton). Rapson (1970) suggests that the RCBP conglomerates are a lag deposit, produced in part by dessication in a subtidal environmental setting. This would appear to explain a large part of the area. As the Wordian sea retreated westward, progressively older subtidally formed breccias would be exposed, to the east. During the course of this study many of the sections of the RCBP showed channel features such as 1-2 metre deep, 3 metre wide scour surfaces; various types of crossbedding; some incomplete fining upward seqeunces; grey-green shale filled channels, well rounded chert boulders (up to 30 cm) in a medium to coarse grained sandstone; cut and fill structures and parallel laminated sandstones. Although some of these channel type deposits are possibly tidal in origin, it is not unreasonable - given the strong suggestion of a subaerially exposed shelf - to suggest that some of these channels were fluvial. A region in the northern part of the study area (Fig. 34) shows many fluvial features. Some cut and fill, cross-stratified, channel deposits were also observed farther south (Section 384), however here the deposits are almost certainly marine as vertical burrow trace fossils are also present. Most of the previously discussed facies developed during the regressive phase, however the phosphate was not likely deposited until the ensuing transgressive phase, and prior to progradation of the Ranger Canyon clastics. Phosphate precipitation was, as in the sand / dolomite facies, either by:

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[63] This author's interpretation of Bushinsky's work

1. direct precipitation as a primary cement infilling the breccio-conglomerate - either directly out of the water column or through interstitial water,
2. phosphatization and mineral replacement of a preexisting cement.

The first explanation accounts for the often "floating clast nature" of the conglomerate. There is however ample petrographic evidence to support the latter process as well, namely: extensive phosphatization of matrix sponge spicules throughout most of the samples, etching and dissolution of quartz grains, and some phosphatization of clastic quartz itself. In addition, most of the breccias and breccio-conglomerates of the Spray Lakes Group (underlying) are cemented with silica, suggesting that perhaps the RCBP zone was also and that this early silica cement was phosphatized during the transgressive period. The geochemical conditions were probably similar to those described for the sand / dolomite facies.

With the Capitan transgression, came the eastern progradation of the Ranger Canyon Formation clastics. Rapson (1970) suggests that the transgression began in the northwest and proceeded south. Rapson has described the Ranger Canyon as primarily sandstones or silty cherts, some phosphorites and dolomites. The Ranger Canyon has been heavily silicified by diagenetic processes, outlined by Rapson (1970), making present day lithologic distinctions difficult, without extensive petrographic study. Rapson described the Ranger Canyon as an eastward prograding series of quartz and gypsum sands. The sands were cemented by carbonate, in shoreline and intertidal areas and by sulfate in supratidal zones. Brines concentrated by refluxion plus local silica enrichment, brought about silicification and silica replacement of much of the Ranger Canyon. A modern analogue envisiged by Rapson was off the Baja California coast where continental clastics and evaporites are prograding over a lág gravel covered surface cut into Miocene age strata. Offshore, phosphates are also forming in the Baja example.

Scattered occurrences of the RCIP zone likely represent similar offshore shelf-margin type phosphates. Nodules and phosphatized sandstones are the predominant phosphate lithotypes.

Toward the early Ochoan time a brief and localized, northern sea level lowering occured, resulting in deposition ofthe RCUP and possibly the MBP conglomeratic zones. These zones are very similar to the RCBP zone and likely formed in a very similar manner.

Mowitch Formation Phosphate Model

A return to higher sea levels, combined with uplift in some northern region, brought on the progradational Mowitch sands into the northern, and possibly as far down as the central, regions (Fig. 15). The depositional environment postulated by McGugan et al. (1968) is basically a continuation of the one put forward for the Ranger Canyon. The Mowitch was apparently not as heavily silicified as was the Ranger Canyon, and the predominant massive sandstone lithology is everywhere apparent. The available evidence suggests a shallow shelf environment for the lower Mowitch, with a gradual deepening of the depositional environment for the upper Mowitch. A deepening is indicated by the *Zoophycus/Spirophycus* trace fossil assemblage, and finer siltstone to shale lithologies, at least in the westernmost sections. Some of these same western sections appear to be unbroken sequences right up into the silty shales of the Triassic Sulphur Mountain Formation. Most other eastern sections in the shelf margin to shelf positions, show a break at the top of the Mowitch marked by the MUP zone. This last sea level lowering corresponds to a worldwide lowering at the end of the Paleozoic (Fig. 31), thought to have been brought on by glaciation in the southern continents (McCrossan and Glaister, 1964).

The MUP zone consists mainly of reworked phosphate pebbles that compositionally look identical to the insitu RCBP, sand/dolomite type facies phosphate. It is likely that a similar environment of deposition as the RCBP - sand/dolomite facies existed in MUP time, and that these phosphatized sandstones were later ripped up, rolled into pebbles, transported and deposited during the regressive phase or were ripped up, reworked, and redeposited during the Triassic transgression.

Spray River Group

Phosphates are not abundant throughout most of the Triassic Spray River Group. Those present consist mostly of *Lingulid* type phosphatic brachiopod shells (Gibson, 1974), thin phosphate pebble intraformational conglomerates, and some pelletal varieties in the Whistler Member. The BPMP, LWMP, and UWMP (Fig. 17) are all intraformational type pebble conglomerates. The Sulphur Mountain Formation, in which all of these horizons are found, is considered by Gibson (1974) to have been deposited in a shallow water, neritic environment, parts of which formed coalescing delta complexes along the Alberta Arch and into the Alberta Trough.

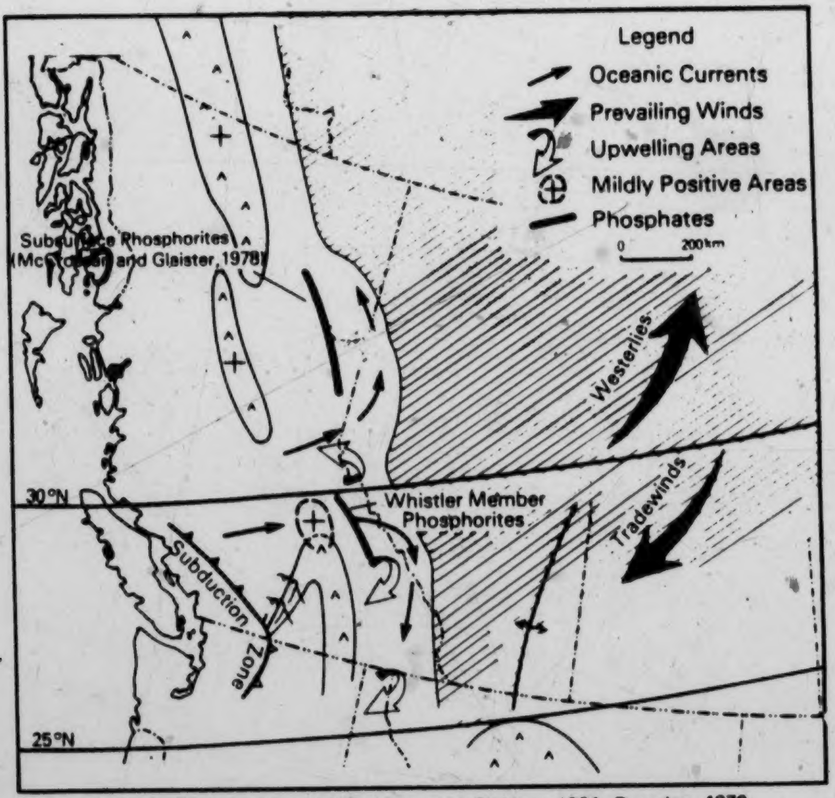
Following a long period of erosion brought on by a low sea level stand (Fig. 31) during the Permian the onset of the Lower Triassic was marked by a global rising of sea level throughout the Lower Triassic. This was followed by a lowering of sea level toward the end of the Lower Triassic (Fig. 31). It is therefore possible that the BPMP zone marks one of these major second order cycle transgressive events. While most of the Vega and Phroso Member consist of very uniform evenly bedded siltstones, the lowermost Phroso is characteristically very argillaceous, organic rich and contains *Palaeophycus heberti* dwelling burrows. This evidence suggests an abyssal environment brought on by a rapid transgressive event. Prograding clastics from the east progressively became the dominate sediment type. A very brief period of phosphogenesis, quickly followed by reworking, took place as this transgressive event occurred, resulting in the sporadic transgressive lag deposit of the BPMP zone. None of the Lower Phroso Member dark, silty shales were found to be phosphatic, and one might expect that they should be. The study area was in a favorable paleolatitude (Fig. 35, 25°N), trade winds would have been blowing off the continent toward the sea promoting upwelling and the shales are organic enough to suggest life was flourishing and a potential source of PO_4^- enrichment in bottom sediments was therefore present. So why is there no significant accumulation of phosphates in the Lower Triassic? Two explanations seem possible:

1. Upwelling was not taking place in spite of all the favorable conditions cited or
2. Upwelling was taking place but rates of clastic sedimentation greatly exceeded any phosphogenesis and any precipitated phosphate was greatly diluted.

The latter explanation is favoured in that some samples tested from the lower Phroso, while not true phosphorites, did show P_2O_5 contents in the 0.50 to 2.0% range (the PMIC zone). This is well above the crustal (0.27%) average, and so suggests some phosphogensis was taking place, but that the diluting effect alluded to earlier was overpowering.

The VMP and LMP phosphate zones (Fig. 17) likely represent brief stillstand times when phosphogenesis could briefly exceed clastic sedimentation, enough to appear as a discrete phosphatic horizon. They may also, in some areas, represent the accumulation of phosphatic *Lingulid* shells.

The Whistler Member marked the beginning of another global sea level rise at the start of the Middle Triassic (Fig. 31). The transgressive event is marked at the base of the Whistler by the LWMP horizon. It is likely that the preceeding regressive event did not subaerially expose the Lower Triassic sediments, but rather this represented a stillstand or non-depositional time. During this stillstand time phosphogenesis may again have had a chance to "catch up" to clastic deposition. The phosphatic material present in the LWMP varies from nucleated and oolitic pellets, pebbles, bones to phosphate cemented siltstones. This assemblage would indicate an oxygenated, fairly active wave, shallow water environment of deposition. This is in sharp contrast to the oxygen-deficient, environment envisiged by Gibson (1974), although numerous fine light grey silty dolomite laminations are conceded by Gibson to represent more oxygenated conditions. Given the obvious fluctuating oxygenated environmental conditions, the nucleated phosphate pellets, thickening of the Whistler Member westward and facies change eastward into the dolomitic siltstones of the Llama Member, and the finely laminated silty dolomite lithology of the Whistler it may be possible to speculate that the Whistler represents an intertidal or subtidal flat deposit along some shallow water area to the west. Intertidal deposited


Legend
Oceanic Currents
Prevailing Winds
Upwelling Areas
Mildly Positive Areas
Phosphates
0
200km
Subsurface Phosphorites
(McCrossan and Glaister, 1978)
Westerlies
Tradewinds
30°N
Whistler Member
Phosphorites
Subduction
Zone
25°N

Paleogeography After; McCrossan and Glaister, 1964, Douglas, 1970, Price and Douglas, 1972, and Irving, 1978.

Figure 35. Paleogeographic reconstruction — Middle Triassic of western Canada

phosphorites have been described by Birch (1980) from South Africa and show many similarities to the Whistler Member phosphates. Many of the South Africa phosphate varieties are nucleated and oolitic pellets with some phosphate cemented siltstones also being present. Birch considers the pelletal phosphates to have been deposited authigenically at the water / sediment interface, and the phosphate in the phosphate-cemented siltstones to have precipitated directly out of the water column or from interstitial waters. From a paleogeogrpahic view (Fig. 35) the Whistler Member phosphates were within a favorable paleolatitude / shoreline position for upwelling to have occured. Phosphorites are also known from the Middle Triassic in the subsurface of northwestern British Columbia (McCrossan and Glaister, 1964).

The UWMP horizon shows an almost identical assemblage of phosphate lithotypes as the LWMP. They were probably formed in a very similar manner as the LWMP. Progradation of the Llama Member clastics and a corresponding drop in sea level (Gibson, 1974) ended the Whistler phosphogenic episode.

The other occurrences of phosphate in the Whitehorse Formation are almost always as phosphatic brachiopod shells - *Lingulid* and *Orbiculid* types (Gibson, 1974). Gibson considers these brachiopods to inhabit shallow marine brackish to near brackish water intertidal to subtidal environments.

Fernie Group

Sinemurian Model

The main phosphorite deposits within the Fernie Group seem to have formed during Lower Sinemurian time. On a global scale, the early Jurassic was the time that Pangea began to break apart and the present day Atlantic Ocean was born. Rifting, that occured between eastern North America and northwest Africa is thought by Hallam (1978) and other workers, to have brought on a major second order cycle of sea level rising throughout the Jurassic (Fig. 19).[44] Along the western coast of North America a subduction zone in central British Columbia is suggested by Monger and Price (1979), producing a series of island arcs (?) and calcalkaline to alkaline volcanics in southwestern British Columbia (Fig. 36). The paleogeography of the Lower Sinemurian shows the study area to be at about 30°N latitude (Fig. 36). This area would probably be influenced primarily by the Trade Wind belt, however the Westerlies were no doubt of more importance in the northern part of the study area. Oceanic nearshore currents likely flowed northwestward in the northern region and southwestward in the southern region (Fig. 36). Southward flowing ocean currents were likely deflected seaward (i.e. westward) by the probably emergent Montania. This seaward deflection, combined with Trade Winds blowing off the continent, would have made the region in southeastern British Columbia and southwestern Alberta, a zone of very intense upwelling (Fig. 36). Desert conditions are implied in southern Idaho, southwestern Wyoming, northwestern Colorado and northeastern Utah, by the Nugget-Navajo Formation aeolian sandstones. The paleoclimate in the study region is less certain, with Nelson (1970) suggesting a very wet, tropical environment. Most authors agree that paleophosphorites all required very slow or no clastic sedimentation. It is likely then that the climate of the southern region of the study area was more influenced by the dry desert conditions to the south, than by possible wetter conditions to the north.

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[44] This rifting was actually likely responsible for the major first order cycle of sea level rise from Jurassic to Upper Cretaceous time.

A long period of post Triassic erosion lasted through to the end of the Hettangian, at which time the Lower Jurasic third order cycle of transgression began. This Lower Jurassic transgression began on a worldwide scale at Hettangian time and is known to contain nine distinct subcycles (4th order?) of sea level rise (Hallam, 1978) (Fig. 19). The fourth order cycle, S1-Figure 19, was likely a rapid transgression throughout the study area. Evidence for this would be: the widespread and uniformly thick Nordegg Member/Formation, black organic rich shales (deep stagnant water) often found at the base of the Nordegg, development of unnucleated, non-oolitic phosphorites immediately above the unconformity,[65] grain flow or similar deep water mass flow deposits very low in the section and the deep water trace fossil *Paleodictyon* found very near to the unconformity. This first S1 cycle transgression was responsible for most of the phosphate deposition, most of the Nordegg and nordegg equivalent members, and possibly the thin (<50 cm)

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[65] This, as will be explained later, suggests that the pellets were not formed in a shallow water environment by rolling wave action.

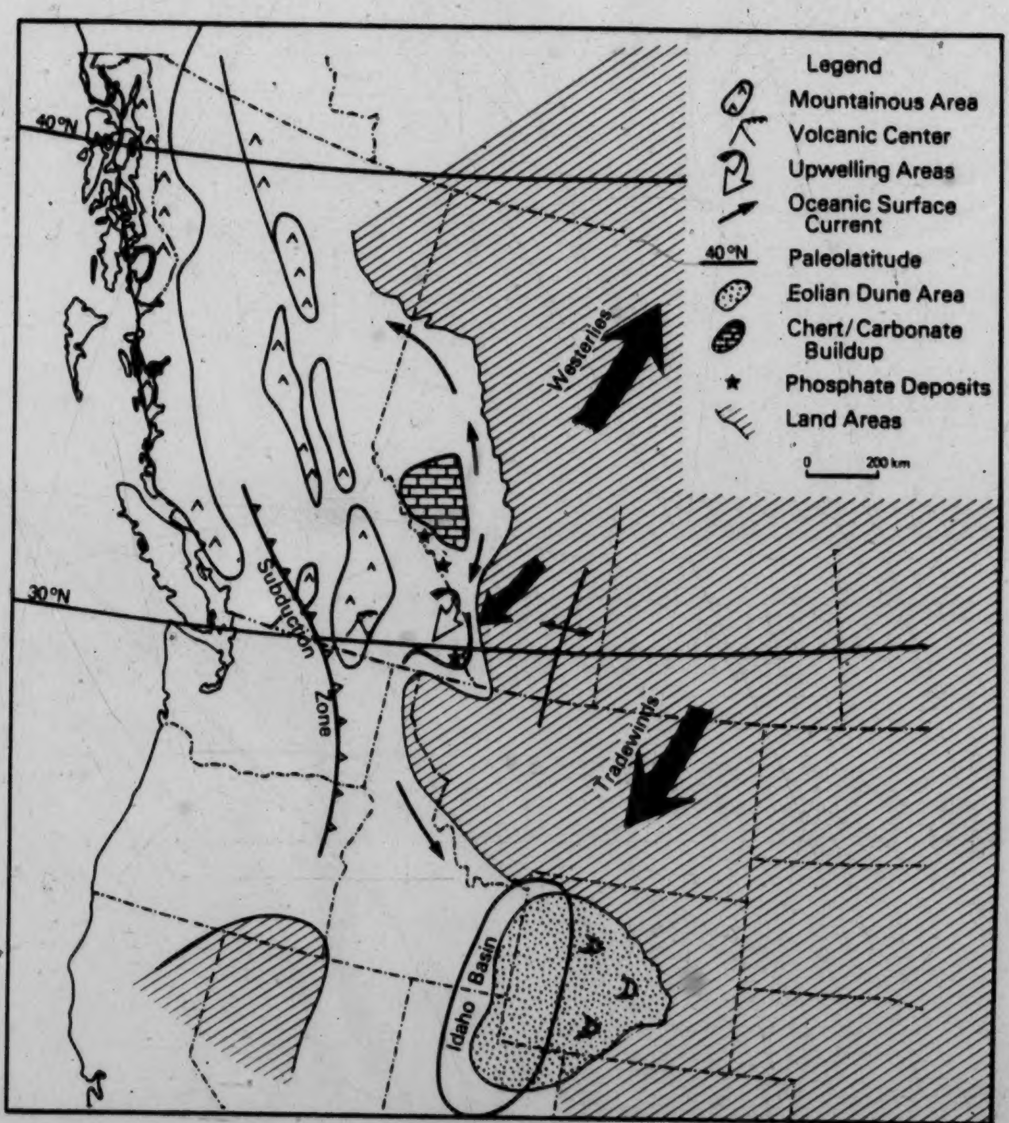
Legend
Mountainous Area
Volcanic Center
Upwelling Areas
Oceanic Surface Current
40°N Paleolatitude
Eolian Dune Area
Chert/Carbonate Buildup
Phosphate Deposits
Land Areas
0 200 km
40°N
30°N
Westerlies
Tradewinds
Subduction Zone
Idaho Basin

Figure 36. Paleogeographic reconstruction of the Lower Jurassic (Lower Sinemurian) in western Canada

transgressive phosphatic sandstone or conglomerate found throughout much of the area. The Lower Sinemurian was evidently a time of extensive volcanism, to the west, and up to six thin, bentonite seams have been observed below the Nordegg Member. The presence of these bentonites and the organic rich shales found below the Nordegg in the central and eastern study area suggest that very quiet stagnant, reducing conditions were established very early on in this western area of the shelf.[66] The Nordegg equivalent, found in the western sections, was probably deposited in a slope to shelf margin position (Fig. 37). Lithologies developed include: black shales, thin cherts, phosphorites and phosphatic mudstones, grain flow deposits (sandstone) and bentonites. The pelletal phosphates were deposited in this shelf-margin facies, always being found in the extreme western sections examined. The pelletal phosphates appear to be in an extremely likely area for upwelling to have taken place. The likelihood of upwelling would seem to diminsh northward as the dominant oceanic current direction became north flowing and the westerly winds blew off the ocean onto the continent. This is reflected in the lithofacies map (Fig. 37) in that phosphate in the Phosphatic Shelf Margin facies, north of about paleolatitude 33° North, is poorly developed, thin and generally of low grade. Those phosphates in the extreme northwest part of the study area contain a lot of phosphate pebble and intraclastic conglomeratic material. These phosphates may actually form alongside of or on top of a possible arch in this area (Fig. 37). On this arch there is very little, and sometimes no Sinemurian age strata present. One locality (section 8) does not appear to have any Toarcian age sediments present either. Dynamic upwelling over this mildly positive feature may have promoted phosphogenesis locally. One of the later Sinemurian transgressions (S2 or S3, Fig. 19) may have reworked it into surrounding sediments. The pelletal phosphates likely formed in fairly deep, quiet, reducing conditions, below effective wave base. Absence of any cross-stratification, the dark organic rich nature of the pellets, the lack of burrowing[67] and an overlying bentonite seam would all support this claim.

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[66] The Nordegg Formation in the subsurface was only studied in a cursory manner, based mostly on the work of McCrossan and Glaister, 1964, and so details of the eastern shelf are sketchy.

[67] The only trace fossil seen in the pelletal phosphates was a single large (2 cm wide) *Thalassinoides(?)* type burrow at the Fernie/Spray River contact.

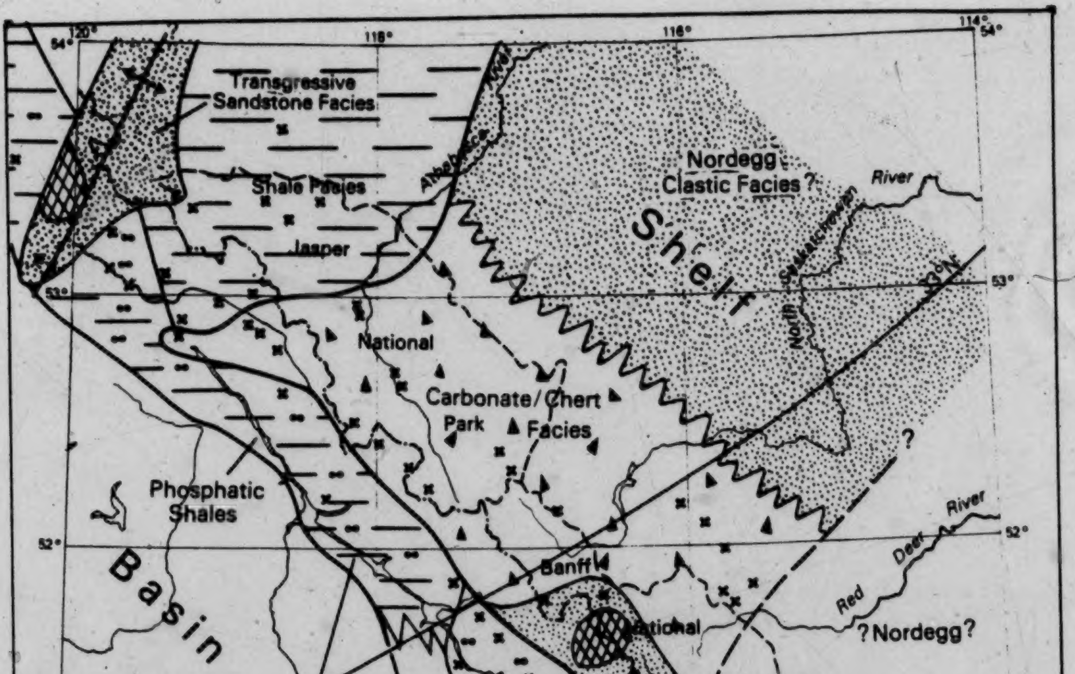
120°
118°
116°
114°
54°
53°
52°
51°
50°
49°
Transgressive Sandstone Facies
Shale Facies
Jasper
Athabasca River
Nordegg Clastic Facies ?
Shelf
North Saskatchewan River
National
Carbonate/Chert Facies
Park
Phosphatic Shales
Basin
Banff
National
Park
Red Deer River
? Nordegg ?
Bow River
Phosphatic Shelf Margin Facies (Nordegg Equivalent)
Pelletal Phosphate
Transgressive Sandstone Facies
Calgary
Legend
Stratigraphic Section
Lower Sinemurian Eroded
0 25 50 km

Figure 37. Lithofacies map of the Lower Sinemurian Fernie Group, Alberta and southeastern British Columbia — Palinspastically restored

Hard bodied invertebrates, including ammonites would suggest that perhaps only the bottom muds were reducing, and that the overlying water column was at least in part, oxygenated. Some of the pelletal phosphates are quartz silt free, while most have some quartz silt matrix, suggesting some areas were winnowed by bottom currents but not to any great extent. The pellets likely formed authigenically below the water / sediment interface, with mild bottom currents sweeping away argillaceous material, but not being strong enough to remove silt size material. The entire sequence is then depicted as:

1. Oceanic currents moving southward along the coast are diverted westward by seaward blowing winds and / or by encountering the mildly positive (perhaps land) area of Montania.
2. Upwelling produces a flourishing of life along the shelf margin raining organic matter to the ocean floor.
3. Organic matter degradation provides PO_4^- in concentrations several hundred times that of normal seawater and phosphate pellets "gels" begin to form.[61] Bottom currents winnow away argillaceous material leaving a silty matrix.
4. Volcanic activity in the Lower Sinemurian deposits a thin bentonite bed above the phosphates that essentially marks the end of phosphogenesis. With the increased volcanic activity may have come increased argillaceous sedimentation from the west, thereby sufficiently diluting phosphate precipitation.

Continental plate tectonic movement became quite rapid during the Jurassic and by Middle Jurassic time the paleolatitude for the southern part of the study area had shifted from 30°N to about 40°N. It could be that this plate movement ended "ideal" phosphogenic conditions.

All the time 1 or 2 metres of pelletal phosphates and shales were accumulating in the Shelf Margin Facies, up to 50 metres of carbonates, cherts and sandstones were accumulating on the Shelf as the Nordegg Member / Formation (Figure 22, Section C-C'). Some of the more western sections of the Nordegg Member (e.g. Section 13, Nordegg, Fig. 22) show characteristic features of Basin Margin type environments as decribed by Cook and Mullins (1983). Large breccia debris flow deposits, thin evenly bedded and shale interbedded limestone and chert and finely laminated, unburrowed siltstones are all seen at Section 13. The regressive phase, between cycles S1 and S2 (Fig. 19), is marked in the Nordegg by a thin conglomerate horizon below the Oxytoma horizon (Fig. 22). The thin Sinemurian phosphatic sandstone bed, termed Transgressive Sandstone Facies (Fig. 37 and Fig. 22 Section D-D') was likely deposited during one or both of the S2 or S3 sea level rises. Phosphatic nodules, pellets, bone debris, was likely reworked and moved eastward and incorporated into shallow shelf nearshore siliclastic deposits. The Upper Sinemurian was brought in by a final Sinemurian sea level rise (S3 Fig. 19) and the multiple bentonite beds were deposited. These bentonite beds (Fig. 22), in the northern region, attest to increased westward volcanic activity, and probably eastward blowing westerly wind conditions. Only one Upper Sinemurian bentonite bed seems present in the southern region, suggesting that this region was still in the Trade Wind belt (Fig. 22, Section B-B').

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[61] Origin from a "gel" state is suggested by several pellets showing compromising boundaries, suggesting a soft state .

Pleinsbachian age strata has only been positively recognized by Frebold (1969) using ammonite guide fossils, in a limited area in the central part of the study area (Fig. 22, Section C-C'). Thus, it would appear that at the regressive phase of cycle S3 (Fig. 19), the seas pulled back considerably over much of the study area. As no sharp breaks have been recognized at this boundary it may be that the Pleinsbachian was merely a time of very slow sedimentation in shallow seaways, and the shelf was not subaerially exposed. The single occurrence of Pleinsbachian pelletal phosphate, Section 385 (Fig. 22), has not been firmly established as Pleinsbachian, and may well be Sinemurian. Assuming a Pleinsbachian age is correct, the pelletal phosphates likely formed in the same way and in the same shelf position as did the BFP zone pellets. Again, these phosphates appear to be linked to the Pleinsbachian sea level rise (Fig. 19).

The Toarcian third order sea level rise was the final one in the more regional second order sea level rise that occured throughout the Lower Jurassic (Fig. 31). Phosphate deposition is very limited throughout most of the study area, excepting in the southernmost Fernie Basin region (Sections 405,406,407) where thick (several meters) sections of low grade (<10% P_2O_5) phosphates seem to be present. This author did not examine these occurrences however, based on the reliable source of data[69], the beds would seem to be Toarcian in age. Thus, it would appear that the phosphogenic period begun in early Sinemurian time likely continued into the Toarcian in the southernmost part of the region. This would agree well with the notion of "ideal phosphogenic" conditions being closely linked to paleolatitude, and one would expect the southernmost part of the study area to "leave" these ideal conditions the latest as the paleolatitude shifted northward. Phosphatic shell beds and occasionally conglomerates horizons are encountered at the Toarcian/Bajocian boundary. The Aallenian stage has not been recognized in the area at all, and is likely a reflection of the major second order cycle sea level drop (Fig. 31). The lithologic distinction between Toarcian and Bajocian shales is quite sharp and distinct[70], and the missing Aalenian stage both suggesting that this sea level lowering may have caused subaerially exposure of the shelf in some areas. Probably throughout the western regions this was not the case, and stillstand conditions of very low sedimentation were predominant. Phosphates found at this contact are likely the result of these prolonged stillstand conditions of very low sedimentation or transgressive sandstone type phosphate material reworked from an earlier Aalenain(?) phosphogenic event.

The Bajocian sea is thought to have risen (second order cycle, Fig. 31) quite rapidly and to also have fallen quite rapidly. The Bajocian sea was widespread, extenting into the Williston Basin and south into the northwestern United States (Frebold, 1957). Two third order cycles are recognized within the Bajocian second order rise, with an intervening sea level drop. This sea level drop separating the two third order cycles, likely resulted in the Rock Creek Member - sensu stricto, sandstones mainly - being deposited. The FRCLP zone may be more a reflection of the first third order cycle in the Bajocian - with sea levels rising, phosphatization of bottom sediments, into nodules taking place as a result of fresh supplies of deep "ocean sink" phosphorous being brought to shallow levels as suggested by Sheldon (1980). The Rock Creek Member, as a sandstone facies, varies considerably throughout the study area. In the Crowsnest Pass area (Fig. 30, Section 202) it is massive, structureless and contains a very sparse marine invertebrate fauna. In this region the Rock Creek Member coarse clastic facies may represent shelf sand deposits. By contrast, the Rock Creek Member sandstones in Kananaskis/Banff area are very thin, but continuous over a large area.[71] These then may represent turbidity current or sheet type sands. The Rock Creek Member sandstones in easternmost-central area (Fig. 30, Section 324) are distinctly heavily oxidized, structureless, and contain no fossils. These sandstones may have been deposited as either beach, subaerially exposed barrier island or perhaps coastal dune deposits. The sandstones of the Rock Creek Member in the central to northern areas attain their maximum clastic development in this area (Fig. 30, Sections 190, 13 and 26). The basal portions show either offshore deeper water shales progressively shallowing upward with the increasing abundance of bioturbation, thin sandstone units[72] or interbedded sandstones and shales showing distinct evidence of tidal influences such as starved ripples, flaser bedding, etc. (Section 190, Fig. 30). The upper sandstone sequences are typically 5 to 10 metres thick, mostly show low angle cross and parallel stratification and are almost always bioturbated. Trace fossils collected indicate a *Cruziana* ichnofacies assemblage i.e. deposition between fair and storm weather wavebase in a shelf setting (pers. comm. G. Pemberton). These sandstone units show sharp upper and lower bases and are interbedded with ironstone-bearing grey shales. The central and northern Rock Creek sandstones would seem also to be similar to the low energy barrier island model of Galveston Island (McCubbin, 1982). Absence of high angle cross-stratification and constant fine grain size would likely exclude any high energy environment. The sequence fits somewhat better into a sublittoral sheet sand setting as described by Johnson (1978). Fine to very fine grain size, interbedded shales, some coarsening up sequences, lack of abundant high angle cross-stratification and erosional marked pebble conglomerate beds would all tend to support a sheet sand model that has perhaps been influenced by storm and wave action. The sequences may of course be a gradation of sheet sands at the base to Barrier Island near the top. This seems partially likely at Section 13 where a possible rooted zone, fossil log and pebble conglomertes appear. Marion (1983) considers the subsurface Rock Creek clastics to have been deposited

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[69] First Nuclear Corporation provided all of the data in this region, unconditionally.

[70] Dark organic, calcareous shales to non-calcareous pyritic gray-rust color shales (Plate 4B).

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[71] Two such horizons can be traced for over 120 kilometers, Fig. 30, Sections 367, 286 and 283.

[72] Some or many of these thin sandstones may have been storm emplaced as attested by their thin development, sharp basal contacts and possible development of hummocky cross-stratification. This latter observation may also be the author's imagination spurred on by the desire to be one of the avant-garde!

> "on a gently sloping, storm dominated shallow marine shelf and were derived from the east."

The phosphate horizon FRCUP lies at the very top of these shelf sandstone sequences and are typically abundant in both belemnites and phosphate nodules. The phosphate nodules likely grew diagenetically sometime after the emplacement of the belemnite-bearing sandstones and appear related to the second, third order Bajocian sea level rise (Fig. 19). The presence of the sandstones, and some shales, in the Rock Creek Member containing belemnites is somewhat enigmatic. The so called "Belemnite Battlefields" are very widespread in outcrop regions of Alberta from Willmore Wilderness Park, where they occur in shales, southward to the Lodgepole area in southeastern British Columbia. They have also been identified and used as a marker horizon in the subsurface of Alberta and Saskatchewan. The very wide spread nature of these concentrated fossil remains would preclude any local accumulation processes, such as beach concentrations. Fossil concentrations due to an unusually favorable environment - such as an oceanic upwelling area or a time of slow sedimentation may have been responsible. Upwelling and slow sedimentation would fit well with the phosphate accumulations, and may well have played a role, however it is unlikely that upwelling occured along the entire coastline of the Bajocian sea. The problem almost begs for a catastrophic event solution. A sudden volcanogenic outpouring of ash is possible, one thin bentonite bed is known from the Rock Creek, however given the thinness of the ash, catastrophe seems unlikely. Storm conditions of hurricane magnitude moving along the coastline is also possible, and would also fit in well with the sedimentological setting of a storm influenced sand sheet model. The answer of course may not be so catastrophic and lie in the simple inability of the belemnite to adapt to a rapidly(?) shallowing environment, brought on by maximum sea level drop at the end of the first third order cycle Bajocian sea level change. Hallam (1978) suggests that Jurassic ammonites, in general, were highly susceptable to extinction, especially at times of regression.

Conclusions

From this study a number of conclusions can be drawn regarding phosphates in Alberta and southeastern British Columbia. In point form these are:

1. Canada, and Western Canada in particular, has a thriving fertilizer industry, producing nearly 1 million t P_2O_5 per year. Phosphate rock, to feed this industry, is obtained entirely from outside Canada, with the import cost for this raw material estimated to be nearly one quarter of a billion dollars. No phosphate rock is presently produced in Canada.
2. Canadian imports of phosphate rock, primarily from the United States, are expected to remain firm unitl the 1990's. At this time the U.S. may start exporting a more upgraded product. By the year 2000, the U.S. domestic demands are expected to equal production capacity and exports to Canada may start to drop off. At this time Canada may have to start looking to other foreign sources of phosphate rock as well as reexamining the Western Canadian phosphates.
3. Although sixteen geological formations, ranging in age from Helikian to Upper Cretaceous, are known to contain phosphates, only four are considered to have any real potential. These four are: Devonian-Mississippian Exshaw Formation, Permian Ishbel Group (Johnston Canyon and Ranger Canyon Formations), and the Jurassic Fernie Group. Given the present land use restrictions in Alberta it is unlikely that any of the Alberta deposits will or can be exploited for several decades to come. Well over 95% of the phosphate deposits in Alberta are within: the two national parks, one provincial park, one wilderness park and the remainder in the Prime Protection Zone of the Alberta government (i.e. no mineral development allowed). The only developable area that contains phosphates is in the Crowsnest Pass region of Alberta. Even if these restricted land use areas could be rezoned - it is doubtful if the Alberta deposits could compete with American or imported phosphate rock until at least the year 2000. The deposits in British Columbia, Fernie Basin, have at several

times in the past been sub-economic and may again be so, prior to 2000, should the price and or demand for phospahte rock rise dramatically.

4. The Exhsaw Formation only has geologic potential for phosphate exploitation in the region north of the Crowsnest Pass. Although individual phosphate beds may grade to greater than 20% P_2O_5, when considered over at least a minimum mineable thickness of one metre, diluted grades are in the 6-12% P_2O_5 range. There is an estimated 1 to 10 million t of insitu Exshaw phosphate in the 6-12% P_2O_5 range north of the Crowsnest area. The Exshaw is in a very difficult mining situation and all geologically favorable areas are within the "Eastern Slopes Prime Protection Zone".

5. The Permian Ishbel Group has its best phosphate potential within the Ranger Canyon Basal Phosphate (RCBP) and within the Johnston Canyon Intraformational Phosphate (JCIP) zones.

   The Johnston Canyon Formation - JCIP zone - is confined to the westernmost Front Ranges south of Banff, Alberta, and has the best potential for development in the southwest Fernie Basin area. Here the grade / thickness combination exceed 13% P_2O_5 over at least 1 metre, and the JCIP is not subject to land use restrictions. Much of the JCIP zone in the southwest Fernie Basin has not been extensively looked at with respect to grades and thicknesses. Most of the JCIP strata exposed in Alberta is within Banff National Park or Kananaskis Provincial Park. A maximum of about 99 million t of JCIP horizon phosphates, with grades likely in the 12-18% P_2O_5 range over at least 1 metre are present in all areas. About 27 of the 99 million t are in Banff National Park, the remainder are in the Fernie Basin, British Columbia.

   The Ranger Canyon Basal Phosphate (RCBP) zone extends from Willmore Wilderness Park south to the Crowsnest Pass area. In most localitites the phosphate bed is 20-100 cm thick with grades varying from 5 to 25% P_2O_5. Taken over a minimum of 1 metre, most of the zone grades in the 6-12% P_2O_5 range. An estimated 224 million t of 6-12% P_2O_5 / 1 metre is present, with 204 million t present in Alberta, the remainder in British Columbia. However none of these 204 million t in Alberta are in land use areas that permit mineral development.

6. The Basal Fernie Phosphate (BFP) zone, within the Jurassic Fernie Group, is estimated to contain 254 million t of 6-12% P_2O_5 / 1 metre within Alberta, of which a possible 8

million t are in potentially exploitable land use areas. British Columbia is estimated to contain 396 million t of 6 to 24% P_2O_5/ 1 metre (or 343 million t of >18% P_2O_5/ 2 metres) in the Fernie Basin area. Grades and thicknesses in general tend to be leaner to the north into Alberta - and richer to the south toward the United States border in the Fernie Basin. The Fernie Basin area may contain over 2 billion t[73] of subsurface phosphates, as the basin is a large synclinal structure with surface outcrops on the east and west flanks. If this subsurface phosphate could prove to be continuous throughout the Fernie Basin, this would represent a vast resource potential - for perhaps future insitu recovery programs.

7. The mean uranium content in phosphates encountered during this study is 34.3 ppm, with a maximum value of 295.1 ppm. Uranium values are highest (40-60 ppm) in the Fernie and Exshaw phosphates, and lowest (6-7 ppm) in the Tunnel Mountain and Whitehorse Formations phosphates. The phosphorous/uranium relationship is weakly linear and is best developed in all samples regardless of P_2O_5 content and in the group of phosphates containing 12-32% P_2O_5 ($r=0.53$ and 0.21 respectively). At best only 28% of the variability in uranium content in these phosphorites can be attributed to P_2O_5 content. Uranium and phosphorous show a stronger positive linear correlation when considered by stratigraphic horizon, with correlation coefficients rising to 0.7 or 0.8 for Permian phosphates.
8. Vanadium is found to be slightly negatively linearly correlated with phosphorous content when all phosphatic rocks are considered ($r=-0.3$). The Ranger Canyon shows some positive linear correlation between phosphorous and vanadium ($r=0.57$). Vanadium values in phosphorites vary from 46 to 446 ppm. Vanadium values up to 2600 ppm are present in non-phosphatic, organic rich shales of the Exshaw and Fernie.
9. Fluorine in phosphate minerals of this study have a mean value of .0855%. Values seem to be highest in the lithotypes: phosphate cement and bones and lowest in the pellet, microsphorite and intraclast lithotypes. Fluorine values show the most variability in the Exshaw and Lower Fernie Formations and least variability in the Sulphur Mountain, Ishbel and Middle Fernie.

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[73] Based on a crude tectangular shape of 74 x 12 km., assuming a 1 metre thickness of BFP over the entire area.

10. Rare earth elements are present in phosphorites of this study in above average abundances when compared to other worldwide phosphorites. In particular the elements: La, Ce, Na, Sm, Eu, Tb, Dy, Ho, Tm, Yb, and Lu are all found in abnormally high amounts.

11. Trace elements in the phosphorites of this study compare similarily to other worldwide phosphorites with enrichments of the elements: Ag, As, Cd, Mo, Ni, Se, U, Zn and Zr.

12. The mineralogy of the phosphorites in this study is transistional beween pure carbonate fluorapatite; francolite and pure fluorapatite. Dahllite is also present in very small amounts, usually as bone and teeth remains.

13. A variety of phosphate petrographic lithotypes have been identified including: pellets - cored and uncored, oolitic, elliptical and structureless varieties; cements - including microsphorite, fluorapatite and francolite cementing sandstone, siltstones and conglomerates; intraclasts; reworked pebbles; nodules and phosphatic fossil material. Most of the pelletal material is thought to have formed authigenically in bottom muds immediately below the sediment/water contact. Cored and oolitic pellets are thought to have formed in a shallow, high energy environment. Microsporite apparently formed in a fairly shallow water environment as well. The other phosphate cements show evidence of both primary authigenic precipitation and of phosphate replacement, in particular the replacement of sponge spicules. Reworked pebbles and intraclasts are previously precipitated phosphate that has been ripped up, rolled and transported some distance. Nodules seem to have formed in place, by diagenetic phosphate replacement of the host sediment. Phosphatic fossils are of two types: those that originally had phosphatic makeup (e.g. *Lingula*) and those whose shells or bones have subsequently been phosphatized.

14. Most of the phosphate occurrrences within the study area seem to be related to worldwide sea level changes throughout the Paleozoic. Most phosphorites are found at unconformities or within early transgressive sequences. This is thought to be due to a global buildup in phosphorous levels in the oceans during low stand periods and a subsequent overturning or bringing to the surface of this large phosporous "sink" during highstand or transgressive periods. This turning over may, if other conditions

are fullfilled, result in phosphate precipitation. Other conditions that seem to be required area: a low (<40°) paleolatitude, all of the major deposits in this study are within this range. Low paleolatitudes put the continents in the Trade Wind belt, which in North American western coastline situations, results in winds blowing parallel to or off the coastlines, seawards. This situation results in coastal upwelling and the possible precipitation of phosphorites. Prominent jutting pennisulas, landmasses or submerged oceanic rises running perpendicular to the western coastline also promote upwelling by diverting coastal currents seaward. This seem to have been the case during several phosphogenic periods in this study with the emergence of Montania to the immediate south. Plate tectonic movement, that not only determine the paleolatitude, but also determines the position of the continents within a particular wind belt seems also to be critical. During the Permian the continent was positioned so that the western coastline was nearly exactly parallel to the prevailing Trade Winds, an ideal situation to promote coastal upwelling. Once coastal upwelling is achieved the remainder of the phosphogenic process is seen as: a prolific fluorishing of surface life forms, life forms subsequent death and decay on the sea bottom, enrichment of sea floor muds with respect to phosphorous, concentration of phosphorus and finally direct authigenic phosphate precipitation or phosphatization within interstitial muds. Bottom currents winnowing away muds, further serves to concentrate the precipitated phosphate while later diagenetic effects such as calcite replacing phosphate tend to dilute the eventual phosphate deposit.

15. The Exshaw Formation contains phosphates in four stratigraphic zones. A thin basal transgressive sandstone / conglomerate containing phosphate pebbles, bones and miscellaneous debris marks the base of the formation. The lower and middle phosphate horizons are primarily pelletal phosphates, found within a cherty black shale member. These units are thought to have formed in fairly shallow water shelf conditions, with upwelling being produced from the slightly positive Montania and from favorable paleolatitudal / geographical continental position. An upper phosphatic bone / pebble conglomerate is sparsely found upon a shallow water silty limestone member and marks a change from regressive to transgressive conditions.

16. Most of the Rocky Mountain Supergroup phosphates are found at well established unconformities throughout the Permian and Pennsylvanian. Most of these unconformitites are thought to be low sea level stands when the shelf was probably subaerially exposed. Phosphate was deposited during the next transgressive sea level rise period under shallow water shelf conditions. Phosphate was likely precipitated authigencially interstitially within sands and dessicated breccio-conglomerates. Some evidence exists to show that microsphorite, deposited in very shallow water conditions i.e tidal or subtidal, was then ripped up and transported seaward. There is also evidence to suport phosphatization of sponge spicules and perhaps and early phase of phosphate cement. The paleolatitude / geographical setting was nearly ideal, at least during the Permian, to promote phosphogenesis. Phosphate within the Johnston Canyon Formation likely formed in deeper shelf marginal positions.
17. The phosphates within the Spray River Group are best developed in the Whistler Member of the Sulphur Mountain Group. The Whistler Member phosphates are primarily nucleated and oolitic pellets and are thought to have formed during a stillstand period associated with a Middle Triassic transgression. A intertidal or subtidal depositional environment adjacent to a western landmass is suggested.
18. The structureless pelletal phosphates of the lower Fernie Group were deposited in a shelf marginal position, primarily during lower Sinemurian time. The Lower Sinemurian saw the beginning of a major global second order cycle of sea level rise that lasted throughout the Jurassic. Upwelling along the western coastline was promoted by low paleolatitude (30°N) and a possibly emergent Montania to the south. Eastern, shoreward, facies equivalents of the interbedded shale and pelletal phosphorites are a thick sequence of cherty carbonates and clastics deposited on the continental shelf. The pellets themselves are not thought to be faecal or phosphatized carbonate / shale in origin, but are thought to have formed authigenically in the interstitial muds below the sediment / water interface. Over much of the study area the Sinemurian is represented by a thin regressive phosphatic lag deposit and represents reworked and probably more shelf positioned phosphates.
19. Phosphates in the Middle Fernie, Rock Creek Member seemed to be associated with

barrier island or a sheet sand sequence brought on by a Middle Jurassic sea level lowering. Phosphate nodules and phosphatized fossils show clear evidence of having formed diagentically by phosphatization processes. The phosphate deposits themselves often occur at the end of this regressive period and the begining of another sealevel rise period. The study area was not within the ideal paleolatitudinal position during Rock Creek time (Bajocian) and the reason for phosphatization at this time is still problematic. All that can be suggested is that the associated sea level rise was associated with one of the aforementioned oceanic turnover periods, which brought on phosphogenesis.

PLATE 1. Outcrop Photographs of Phosphate Bearing Strata

A. Typical structural / stratigraphic / topographic setting of phosphate-bearing units in the Cordilleran Front Ranges. Intermountain recesive areas - Fernie Group, Western "backsides" of Ranges - Spray River, Spray Lakes and Ishbel Groups (extreme right). Major thrust fault at the rock treeline contact - extreme left. Willmore Wilderness Park, Alberta.

B. Typical structural / stratigraphic / topographic setting of Exshaw Formation - Front Ranges. Elbow River area east of Kananaskis Park.

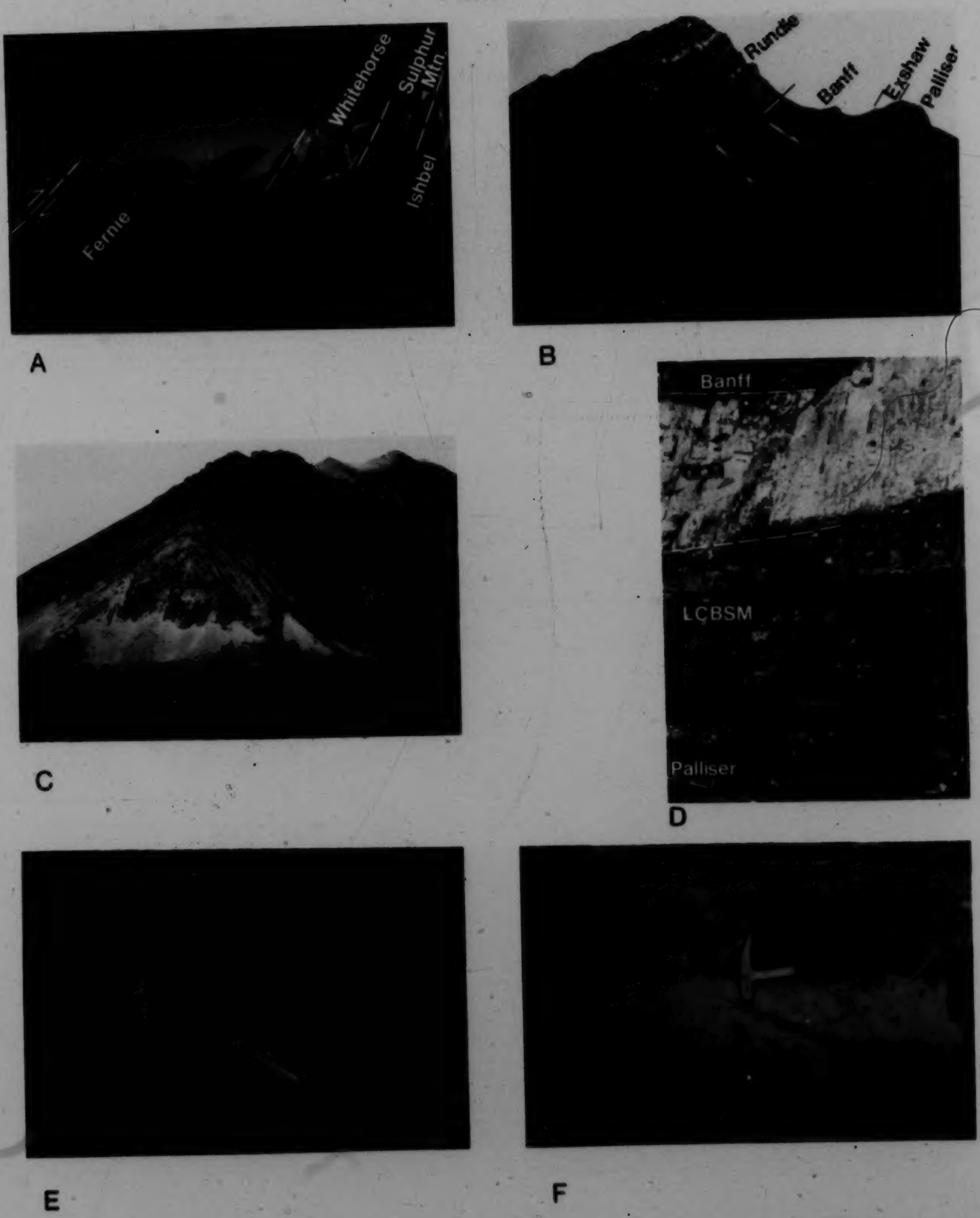
C. Distinctive reddish-brown weathering Sulphur Mountain Formation (Triassic) overlying folded Rocky Mountain Supergroup (Permo-Pennsylvanian). Panther River area Banff National Park.

D. Exshaw Formation outcrop near Canmore-Mt. Rundle Gap - Section 249. Palliser Formation - extreme lower left, LCBSM - lower cherty black shale member, ULM - upper limestone member. Person at bottom for scale.

E. Upper phosphate horizon - Exshaw Formation at Job Creek Section 37. Phosphate nodules and bone remains on uppermost bedding plane.

F. Johnston Canyon Interformational Phosphate (JCIP) at Kananaskis River Canyon Campground - Section 295. Phosphate pebbles and intraclasts showing some graded bedding, set in a siltstone matrix. Point of hammer points "up" stratigraphic section.

Plate 1


Whitehorse
Sulphur Mtn
Ishbel
Fernie
A
Rundle
Banff
Exshaw
Palliser
B
C
Banff
LCBSM
Palliser
D
E
F

Coloured Pictures

PLATE 2. Outcrop Photographs of Ishbel Group

A. **Trace Fossil *Zoophycus*** - bedding plane view. Little Elbow River Headwater - Section 278, top of Johnston Canyon Formation.

B. Typical exposure of Ishbel Group in Alberta, represented by Ranger Canyon and Mowitch Formations and Ranger Canyon Basal Phosphate horizon (RCBP). Recessive weathering Sulphur Mountain Formation overlies Mowitch Formation. RCBP occurs immediately below greenish-colored Ranger Canyon Formation. Monoghan Creek-South Ridge, Section 113. Scale: The Ranger Canyon Formation is about 20 m thick.

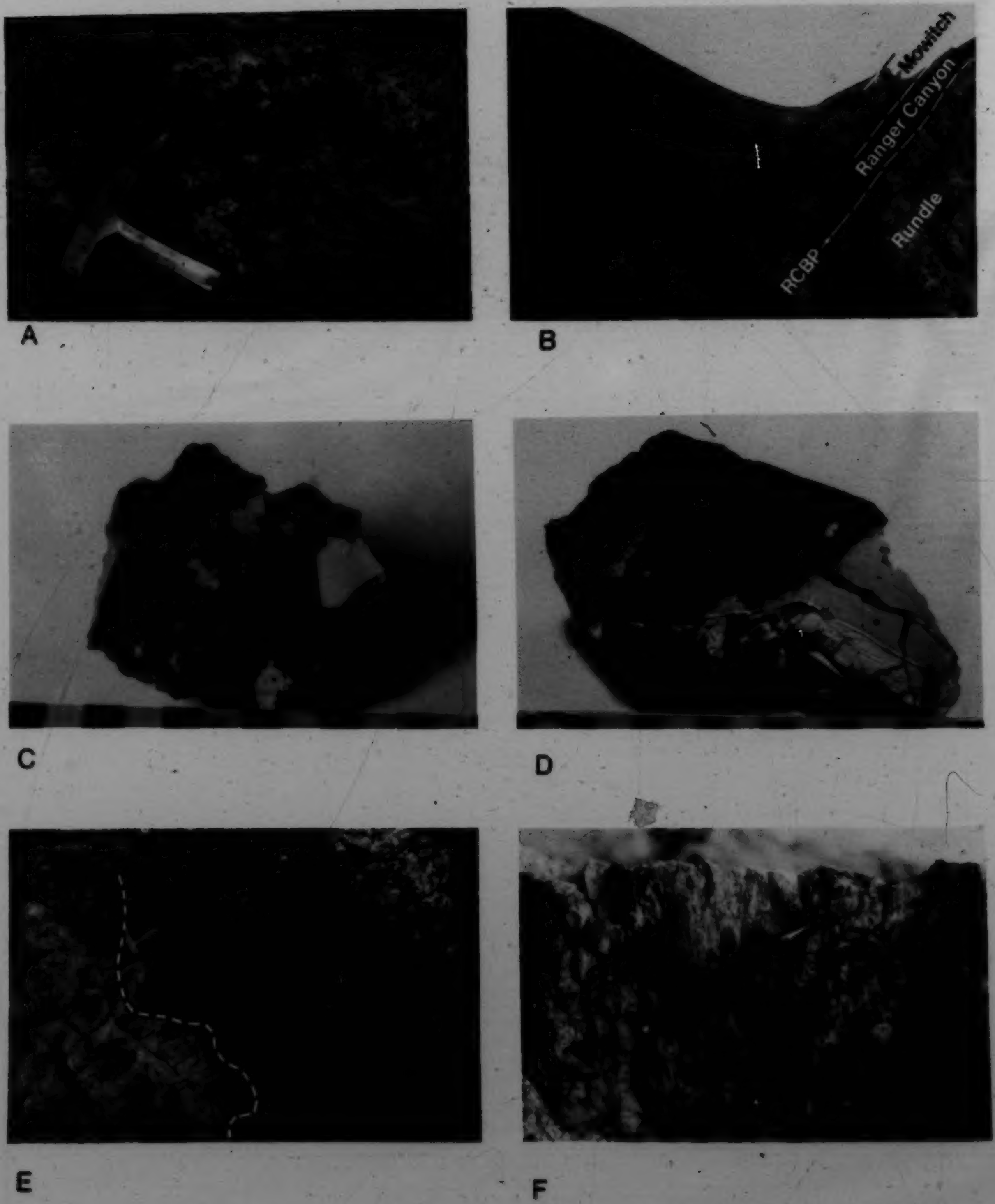
C. Ranger Canyon Basal Phosphate (RCBP) handspecimen showing a typical chert/dolostone breccia cemented by dark black phosphate. Scale in centimetres. Two O'Clock Creek, Section 1.

D. Ranger Canyon Basal Phosphate (RCBP) handspecimen showing reworked, black, phosphate pebbles, imbricately lying in a coarse-grained sandstone matrix. Pebbles overlie buff-colored Rundle Group dolomite; the dolomite shows a possible dessication crack. Scale in centimetres - Southesk Pass-Jasper National Park Section 64.

E. Base of Ranger Canyon Formation (dark colored) showing 30 cm deep scour surface into underlying (light colored) Tunnel Mountain Formation (?). Highway 11 - Roadcut, Section 71.

F Bedding plane view of *Rosselia* trace; end of pencil and *Planolites beverleyensis* trace; lower left corner. Fossils from the Ranger Canyon Basal Phosphate zone - Section 71, Highway 11 Roadcut.

Plate 2


Mowitch
Ranger Canyon
Rundle
RCBP
A
B
C
D
E
F

Coloured Pictures

PLATE 3. Outcrop Photographs of Rocky Mountain Supergroup , Spray River Group, and Fernie Group

A. Rundle Group, Rocky Mountain Supergroup and Sulphur Mountain Formation. Sulphur Mountain shows lower dark silty shale unit that is sometimes phosphatic (BPMP), Phroso and Vega Members. Southesk River, Jasper National Park, Section 66.

B. Spray River Group exposed on a ridge close to Goat Creek Headwaters - Section 35.

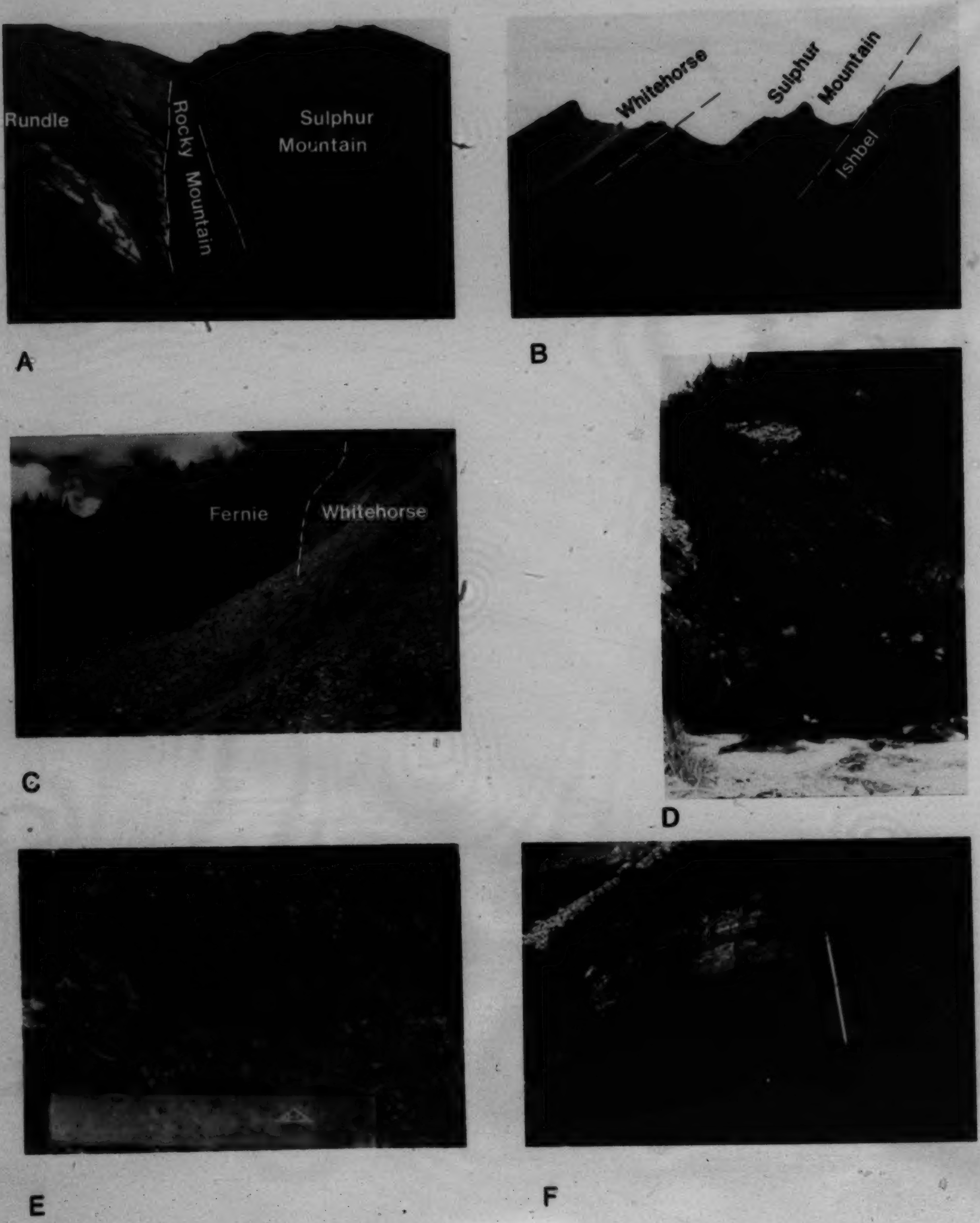
C. Nordegg member equivalent, Fernie Group, western phosphatic / fine clastic facies (dark recessive shales) - overlying resistant light colord Whitehorse Formation. Section of Fernie exposed is approximately 10 m thick. Goat Creek Headwaters - Section 19.

D. Nordegg Member of Lower Fernie exposed at Whitehorse Creek, Section 13 near Cadomin, Alberta. Eastern carbonate / coarse clastic facies. Woman's head is at the top of the Whitehorse Formation, pack is within the NMLS phosphate zone, rythmic, shaly and evenly bedded cherty limestones passing upward into more thickly bedded cherty limestones above the NMLS zone.

E. Sinemurian index fossils *Arnioceras sp?*. Fossils found within the Basal Fernie phosphate zone. Section 10 - Goat Creek Headwaters. Identification by C.R. Stelck, University of Alberta.

F. Basal Fernie Phosphate zone of recessive pelletal phosphorites - at and immediately below 1.5 m stick - Fording River, British Columbia - Section 223.

Plate 3


Rundle
Rocky Mountain
Sulphur Mountain
A
Whitehorse
Sulphur Mountain
Ishbel
B
Fernie
Whitehorse
C
D
E
F

Coloured Pictures

PLATE 4. Outcrop Photographs of Fernie Group and Thin Section of Wolverine Point Formation Phosphate

A. Basal Fernie Phosphate zone of resistant, thin, phosphatic conglomerate. Bighorn Creek Falls - Section 327. Bedding plane view of phosphate pebbles and gamma spectrometer used in detecting radioactive phosphate zones.

B. Jurassic Fernie Group, Rock Creek Member reddish-brown shales (upper left) overlying dark, organic Paper Shales (lower right). Blackstone River North, Section 26. Exposd Paper Shales are approximately 5 m thick.

C. Jurassic Fernie Group, Rock Creek Member, coarse clastic facies, showing two resistant sandstone ridges, separated by up to 15 m of shale. Whitehorse Creek - Section 13 near Cadomin, Alberta.

D. Jurassic Fernie Group, Rock Creek Member, Rock Creek Upper phosphate zone at Whitehorse Creek - Section 13 near Cadomin. Mixture of belemnites, bivalves and phosphate nodules, set in an iron-rich sandstone.

E. Trace fossils from the Rock Creek Member, Fernie Group, Middle Jurassic. Upper left - *Planolites beverleyensis* , lower left - *Rhizocorallium*, lower right - *Gyrochorte*. Identification by G. Pemberton, Alberta Geological Survey.

F. Helikian Wolverine Point Formation showing zoned fluorapatite crystals (gray-green birefringes) cementing a dacitic tuff. Highly birefringent minerals are devitrified volcanic shards. Crossed nicols. Photo courtesy J. Wilson, Alberta Geological Survey.

Plate 4

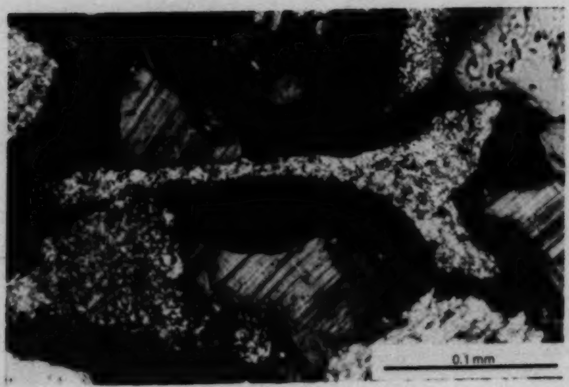
A

B

C

D

E



F

Coloured Pictures

PLATE 5. Thin Section and Scanning Electron Micrograph of Exshaw and Ranger Canyon Formations Phosphates

A. Basal sandstone member of the Exshaw Formation showing phosphatic pellets (PE), intraclasts (I) and bone remains (B). Plain light.

B. Middle phosphate horizon of the Exshaw Formation north of Crowsnest Pass showing tightly packed, bleached, pellets. Many pellets showing compromising boundaries. Plain light.

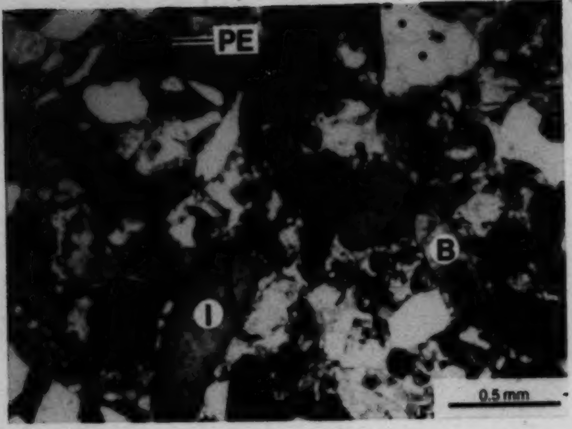
C. Middle phosphate horizon of the Exshaw Formation south of Crowsnest Pass showing microsphorite (M) set in a hematite cement (H), structureless pellets (SP) and quartz-cored nucleated pellets (NP), loosely packed in a chert cement. Plain light.

D. Upper phosphate horizon of the Exshaw Formation showing nucleated pellets (NP), structureless pellets (SP), bone remains (B), intraclasts (I), and phosphate cement (C), set in a predominantly calcite cement. Plain light.

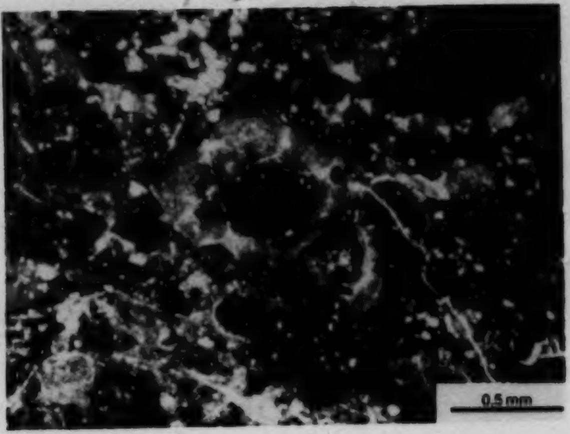
E. Primary fluorapatite cement (C1, C2 and C3 variety) showing very fine crystal size and anhedral crystal shape. Ranger Canyon basal phosphate horizon. Scanning electron micrograph.

F. Primary fluorapatite cement (C1, C2 and C3 variety) showing slightly larger crystal size and more euhedral shape than in Plate 5E, crystals are in the 300 to 400 nm range. Scanning electron micrograph.

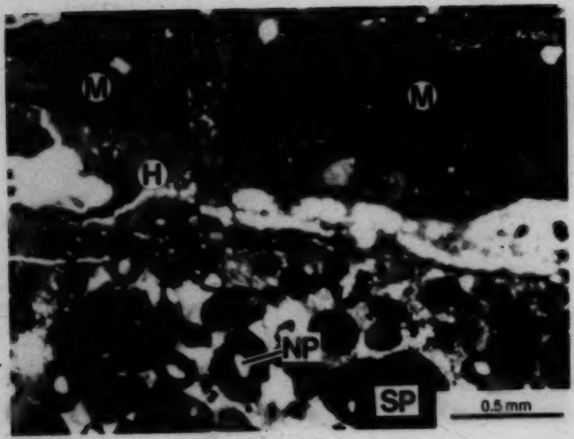
Plate 5



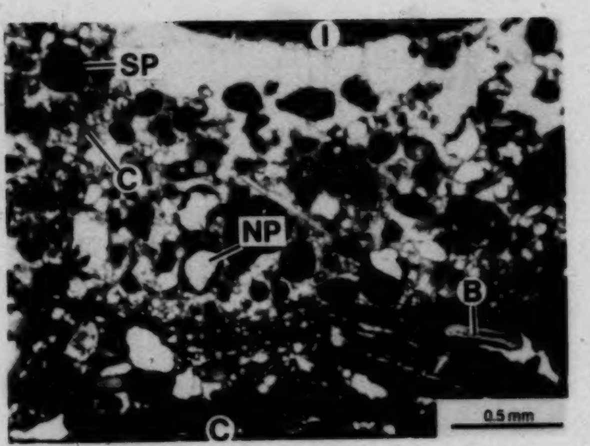
A



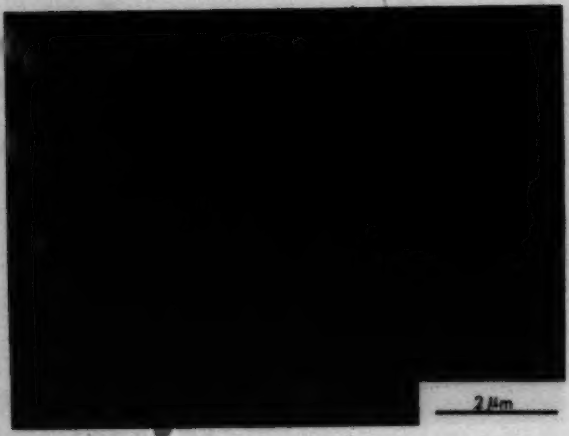
B


M
M
H
NP
SP
0.5 mm

C


I
SP
C
NP
B
C
0.5 mm

D



E

F

Coloured Pictures

PLATE 6. Thin Section and Scanning Electron Micrographs of Ranger Canyon Formation Phosphates

A. Scanning electron micrograph of euhedral francolite laths up to 10 nm long. Ranger Canyon basal phosphate zone.

B. Kananaskis Interformational phosphate showing phosphate pebble (PE), shells (S) and light brown fluorapatite cement between quartz grains. Plain light.

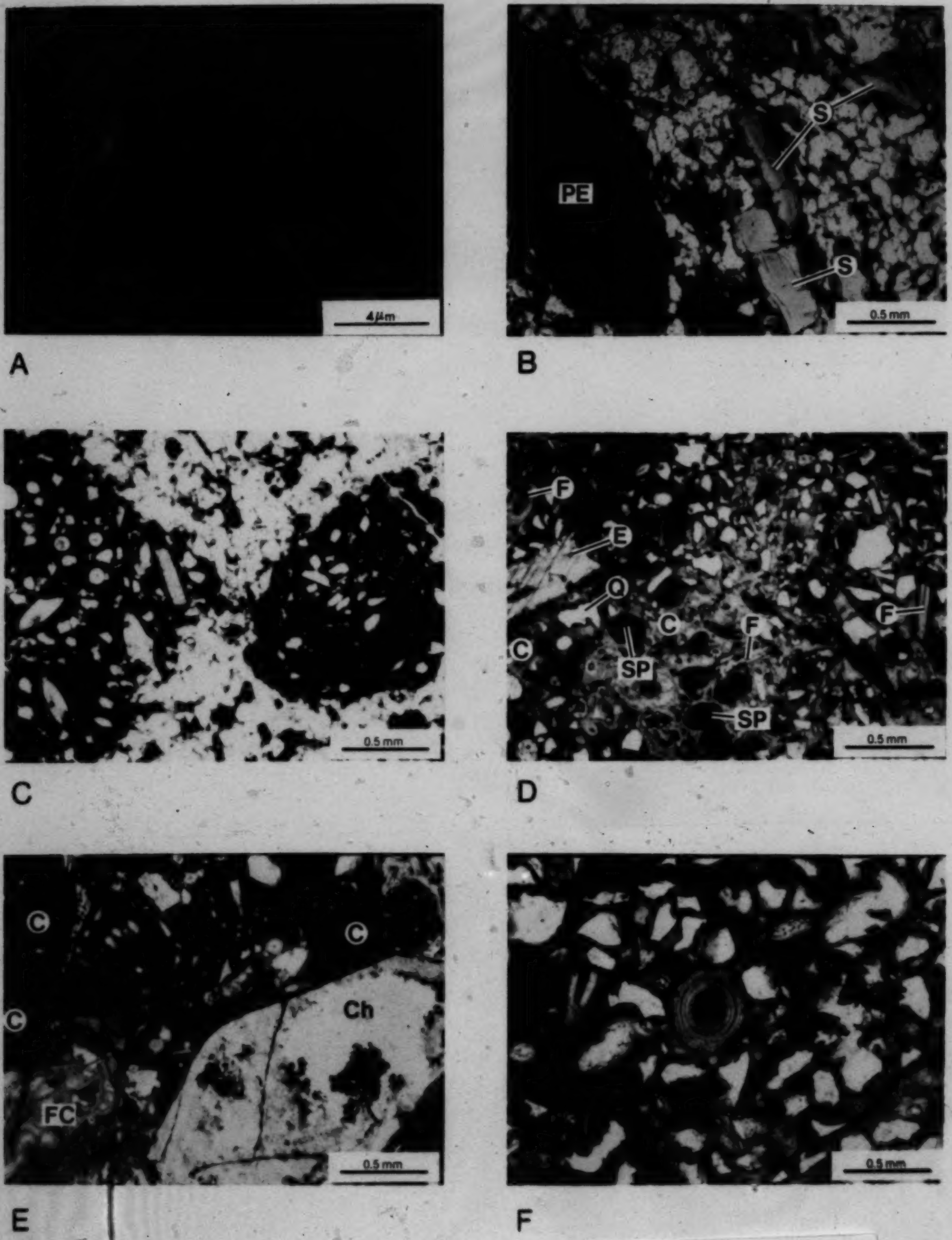
C. Johnston Canyon Intraformational phosphate zone showing two intraclasts of C3 type primary fluorapatite-cemented siltstones. Intraclasts are themselves in a siltstone. Plain light.

D. Johnston Canyon Upper phosphate zone showing a variety of phosphate petrographic textural forms. Francolite sponge spciule remains (F), francolite cement (C) and structureless pellets (SP). Echinoderm fragments (E) and etched quartz grains (G) are also present. Plain light.

E. Ranger Canyon Basal phosphate breccio-conglomerate showing francolite cement (FC), large chert clasts (Ch), CI type fluorapatite cement (C). Plain light.

F. Ranger Canyon Basal phosphate sandstone-hosted phosphate showing oolite (center of photo), francolite and C2 type fluorapatite cement (light and dark brown areas), and floating etched quartz grains. Plain light.

Plate 6


4µm
A
PE
S
S
0.5 mm
B
0.5 mm
C
F
E
Q
C
C
F
F
SP
SP
0.5 mm
D
C
C
C
Ch
FC
0.5 mm
E
0.5 mm
F

Coloured Pictures

PLATE 7. Thin Section and Scanning Electron Micrographs of Ishbel Group Phosphates

A. Francolite cement (F) and francolite-replaced sponge spicules (S) in the Mowitch basal phosphate zone. Plain light.

B. As in plate 7A, crossed nicols showing fibrously radiating francolite within spicules and around quartz grains.

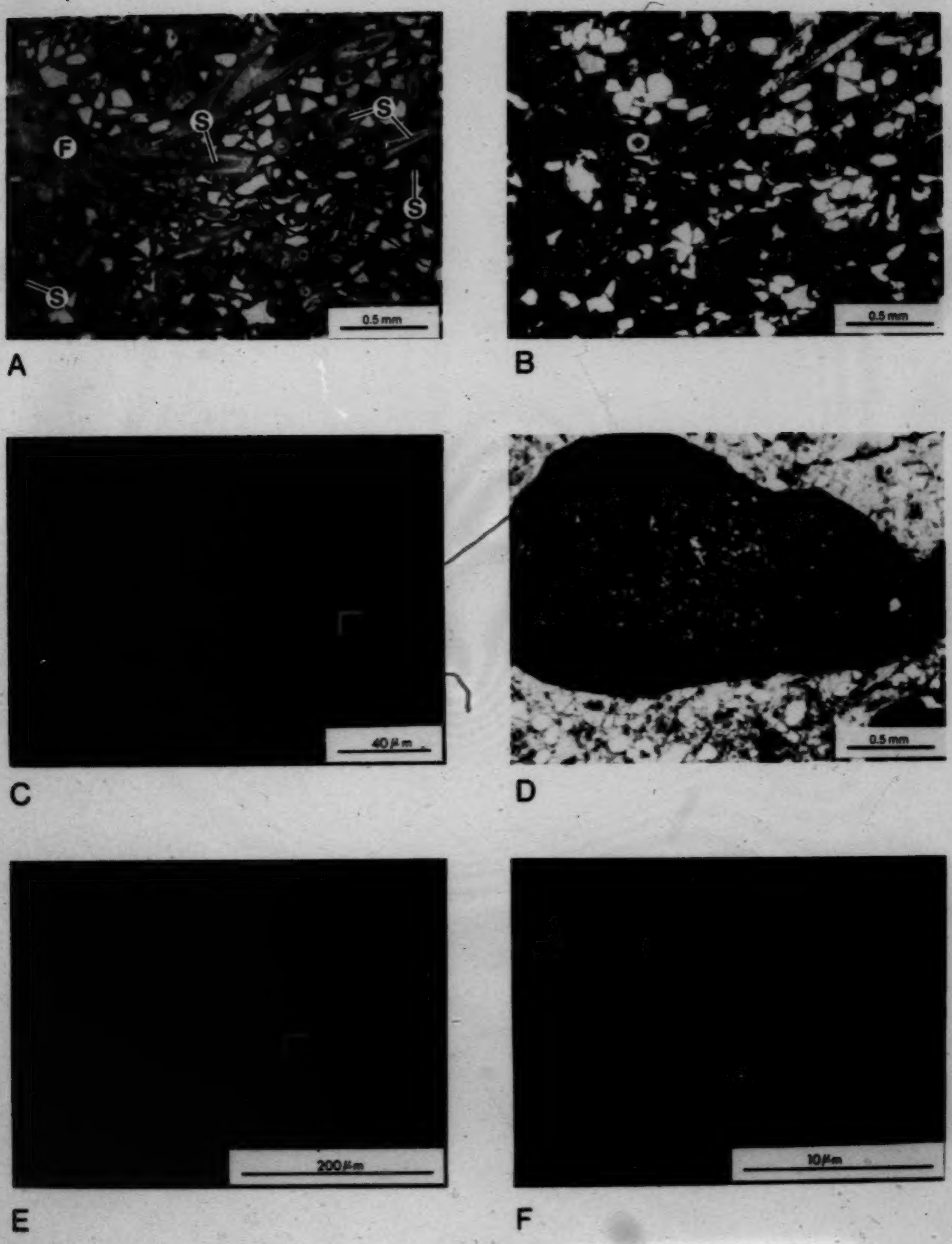
C. Scanning electron micrograph of francolite-replaced sponge spicule (note arrow) in a very finely crystalline francolite.

D. Ranger Canyon basal phosphate zone showing single, reworked phosphate pebble. Pebble is largely composed of francolite-replaced sponge spicules. Plain light.

E. Scanning electronic micrograph of phosphate pellet from the Ranger Canyon basal phosphate zone. Arrow marks area enlarged in plate 7F.

F. As in plate 7E, area enlarged near arrow on plate 7E showing platelet-like structure of the pellet.

Plate 7


S
F
S
S
S
0.5 mm
A
0.5 mm
B
40 μm
C
0.5 mm
D
200 μm
E
10 μm
F

Coloured Pictures

PLATE 8. Thin Section and Scanning Electron Micrographs of Sulphur Mountain Formation Phosphates

A. Phosphatic *Lingula* shell remains (S) in a dolomitic siltstone of the Whistler Member, Sulphur Mountain Formation. Crossed nicols.

B. Scanning electron micrograph of phosphatic *Lingula* shell fragment. Arrow shows the layered structure of the shell.

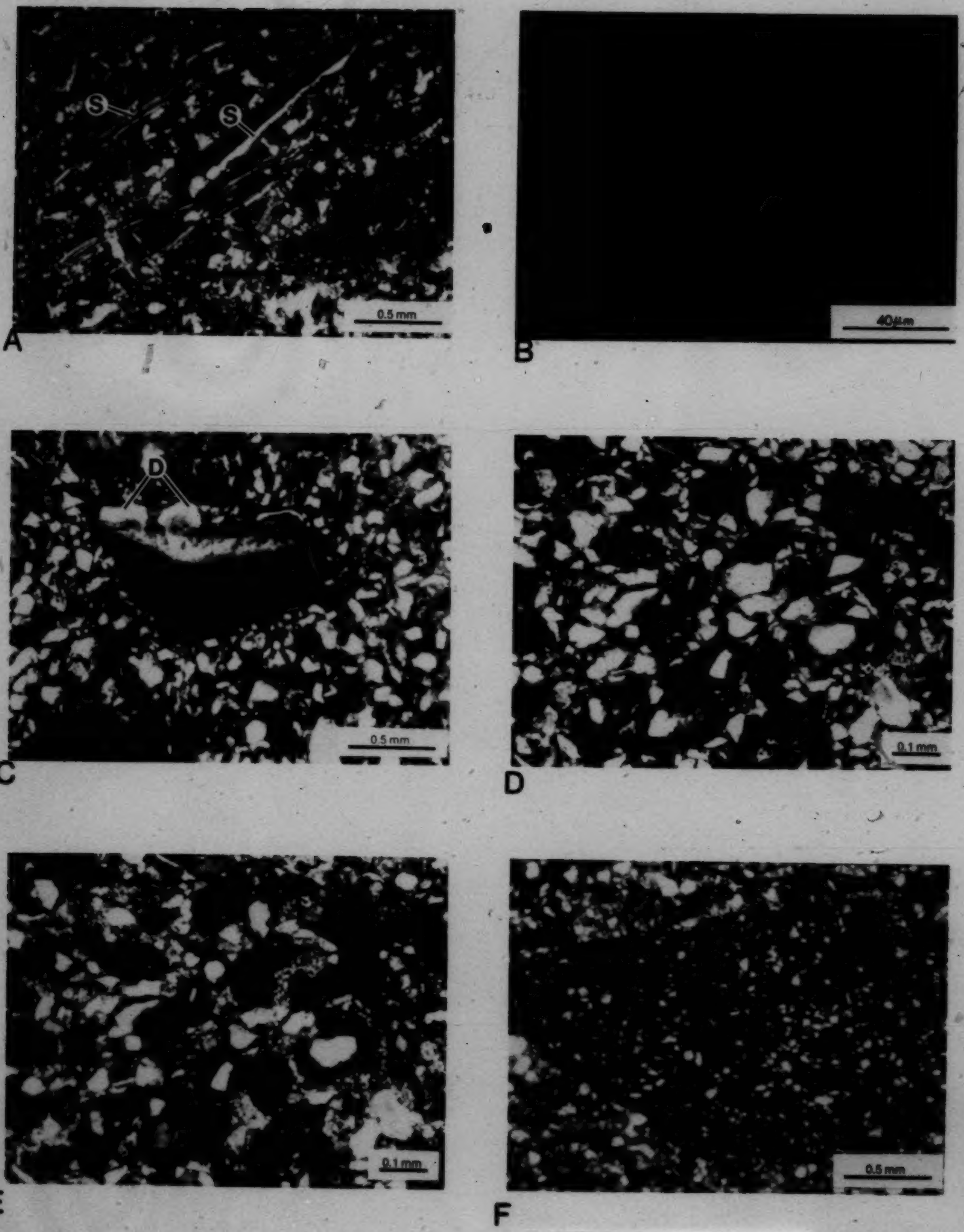
C. Jaw bone (?) fragment showing fluorapatite bone material (brown and yellow color - center), and white dahllite-capping teeth remains. Plain light.

D. Nucleated pellets cored with quartz, minor structureless pellets, set in a dolomitic siltstone of the Whistler Member, Sulphur Mountain Formation. Plain light.

E. As in plate 8D, crossed nicols. Pellets becoming nearly isotropic.

F. Diagenetic phosphate nodule (light brown) from the Whistler Member, Sulphur Mountain Formation, within a silty dolomite. Note the similarity of quartz grain size within and outside the nodule. This evidence supports a diagenetically grown interpretation for the nodule. Plain light.

Plate 8


S
S
0.5 mm
A
40µm
B
D
0.5 mm
C
0.1 mm
D
0.1 mm
E
0.5 mm
F

Coloured Pictures

PLATE 9. Thin Section and Scanning Electron Micrographs of Fernie Group Phosphates

A. Tightly packed structureless pellets from Basal Fernie phosphate zone showing some bleaching (B) due to weathering and several pellets showing compromising boundaries (C). Plain light.

B. Scanning electron micrograph of Basal Fernie phosphate zone pellet showing 50 to 100 nm thick platelets (see arrow) of fluorapatite.

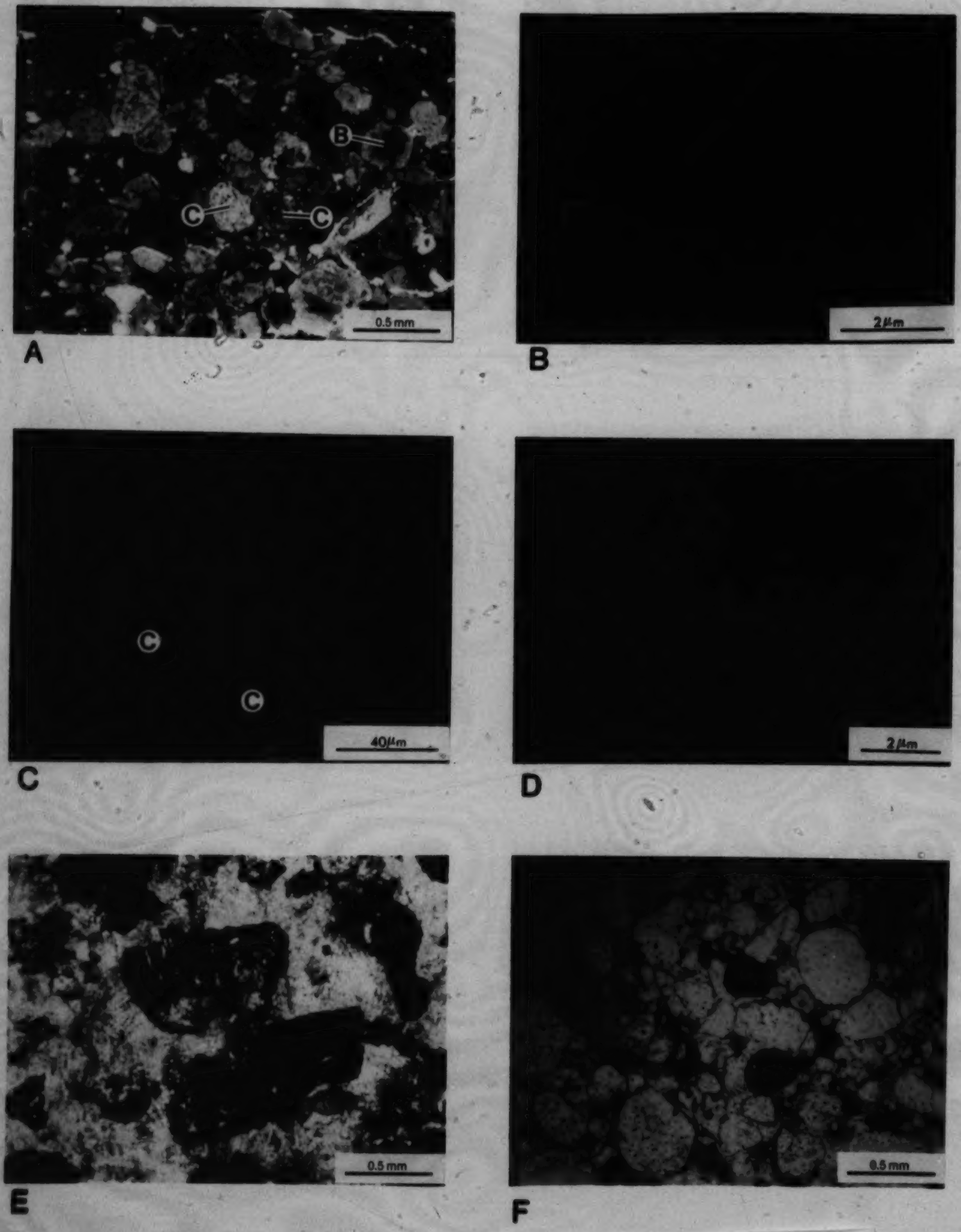
C. Scanning electron micrograph of three Basal Fernie phosphate zone pellets. Calcite (C) forms the cement between the pellets.

D. Scanning electron micrograph of center pellet, plate 9C, showing anhedral, very finely crystalline fluorapatite.

E. Loosely packed phosphate pellets from the Basal Fernie phosphate zone - western shelf margin facies, cemented with and being replaced by calcite. Crossed nicols.

F. Isotropic, structureless pellets from the Basal Fernie phosphate zone - eastern shelf facies. Quartz grains are well rounded and are cemented with quartz overgrowths. Plain light.

Plate 9


B
C
C
0.5 mm
A
2 µm
B
C
C
40 µm
C
2 µm
D
0.5 mm
E
0.5 mm
F

Coloured Pictures

PLATE 10. Thin Section Micrographs of Fernie Group Phosphates

A. Irregularly shaped phosphate structureless pellets set in a poorly sorted, subangular, very fine grained sandstone. Basal Fernie phosphate zone - eastern shelf facies. Crossed nicols.

B. Phosphate intraclast pebble conglomerate - Basal Fernie phosphate zone - northern region. Intraclasts are rich in quartz detritus. Plain light.

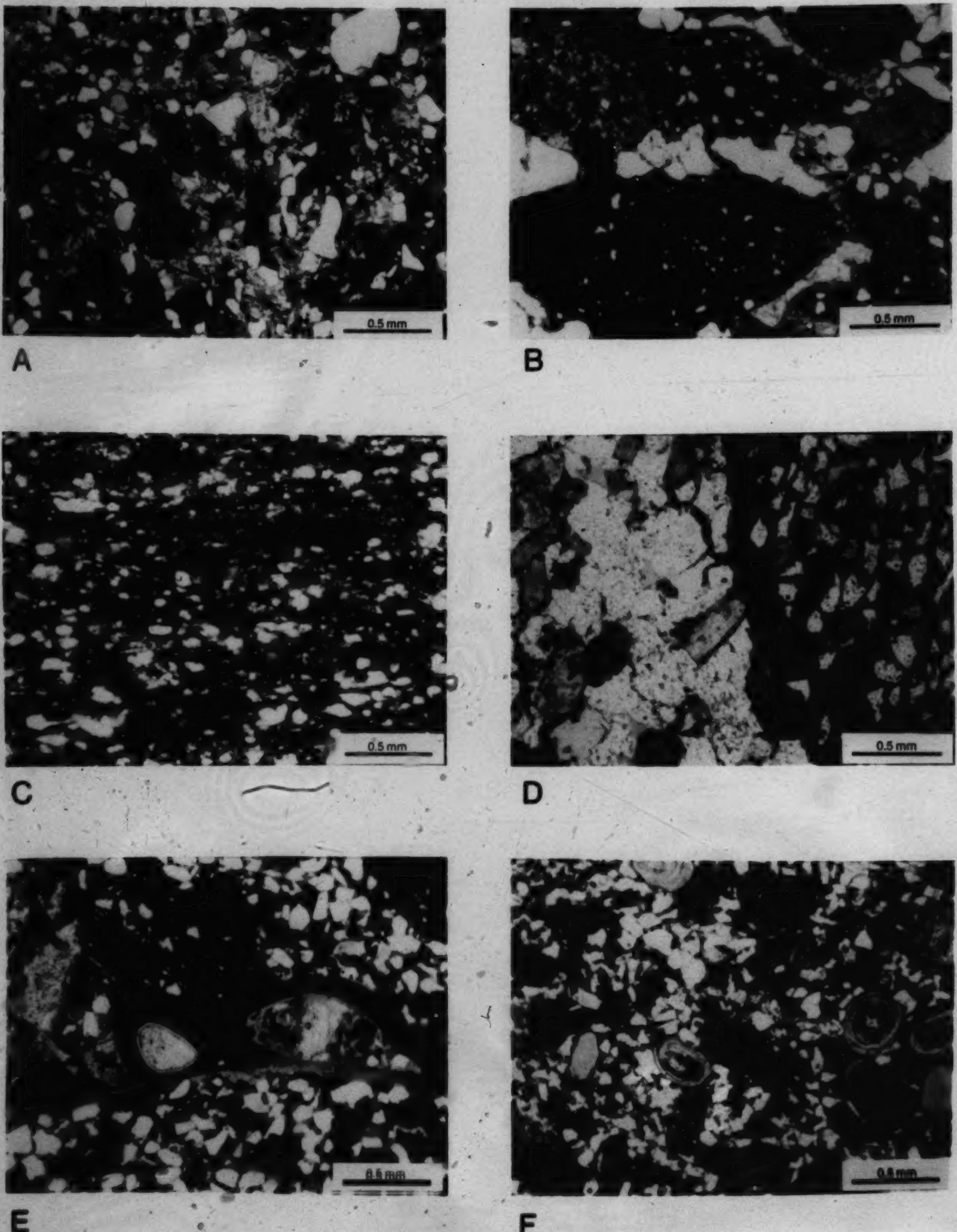
C. Elongate phosphate pellets set in a silty, calcareous shale. Lower Fernie Group - Basal Fernie phosphate zone. Plain light.

D. Phosphate nodule (right side of photo - light brown) growing in a calcareous, fine-grained sandstone, Rock Creek Upper phosphate, Fernie Group. Plain light.

E. Gastropod shell completely phosphatized by francolite. Rock Creek Upper phosphate zone, Fernie Group. Plain light.

F. Oolitic pellets set in a fine-grained, calcareous sandstone of the Rock Creek Upper phosphate zone, Fernie Group. Dark layers within pellets are pyrite. Plain light.

Plate 10


0.5 mm
A
0.5 mm
B
0.5 mm
C
0.5 mm
D
0.5 mm
E
0.5 mm
F

Coloured Pictures

PLATE 11. Scanning Electron Micrographs and X-ray Mapping of Fernie Group Phosphates

A. Scanning electron micrograph of a semi-polished sample of Basal Fernie phosphate pelletal phosphorite using secondary electron imagery. Phosphate pellets (dark) in a barite / calcite cement.

B. Same as in plate 11A, utilizing backscattered electron imagery, which produces better definition - as varying shades of gray - of elements present. The higher the average atomic number of the mineral (i.e. greater density), the lighter tone of gray or white.

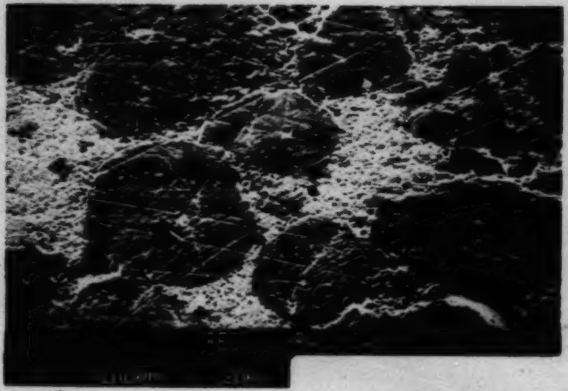
C. Same as in plate 11A, X-ray mapping of phosphorous in the sample. White dots show greatest concentration of phosphorous.

D. Same as in plate 11A, X-ray mapping of calcium in the sample. Calcium is found within the pellets and within the cement and is therefore not a diagnostic element to use in differentiating mineral elements out in this sample.

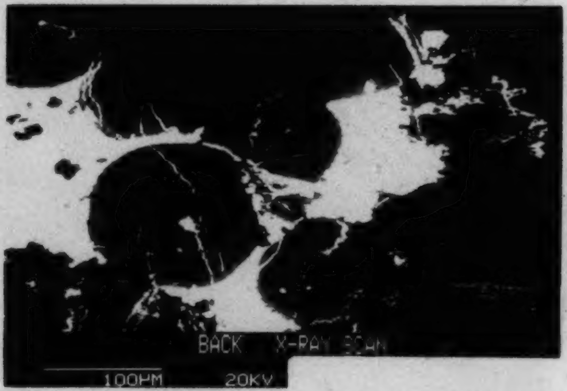
E. Same as in plate 11A, X-ray mapping of silicon in the sample. Silicon is found as detrital quartz in both the cement and within the pellets.

F. Same as in plate 11A, X-ray mapping of barium in the sample. Barium is found exclusively within the cementing regions as barite.

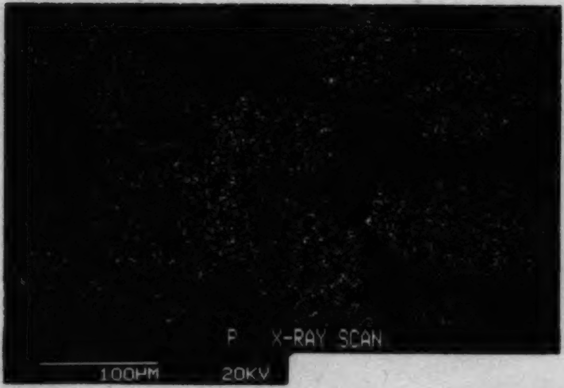
Plate 11



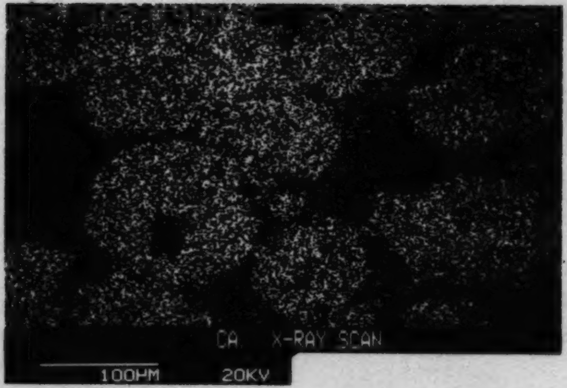
A


BACK X-RAY SCAN
100µM
20KV

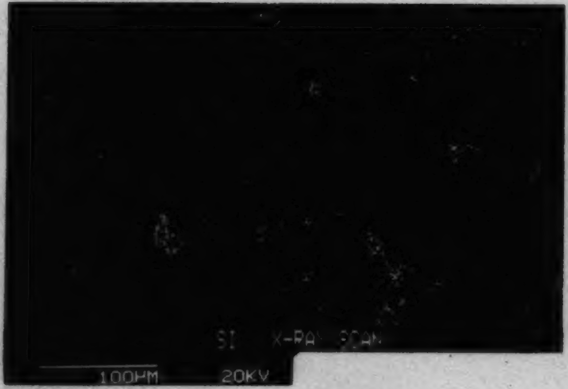
B


P X-RAY SCAN
100µM
20KV

C


CA X-RAY SCAN
100µM
20KV

D


SI X-RAY SCAN
100µM
20KV

E

BA X-RAY SCAN
100µM
20KV

F

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Appendix 1. Locations of Stratigraphic Sections Used in This Study

APPENDIX 1. Locations of Stratigraphic Sections Used In This Study.

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
1	Alberta Geological Survey	52 850 115 2750	51 5900 115 4600	83B3E	Prairie Creek
2	Alberta Geological Survey	52 500 115 5400	51 5000 116 3300	83B4E	Ram River-West of Falls
3	Alberta Geological Survey	52 450 115 5900	51 4700 116 4400	83B4E	Ram River-First Ranges
4	Alberta Geological Survey	52 675 115 5675	51 4800 116 3300	83B4W	Lynx Creek-Headwaters
5	Alberta Geological Survey	52 2075 115 4550	52 1000 116 300	83B5W	Brazeau Range-South
6	Frebold-1957	52 1575 115 3350	52 500 115 5400	83B5E	Fall Creek
7	Alberta Geological Survey	52 5900 117 2100	52 3600 118 200	93C14W	Whitehorse Creek
8	Alberta Geological Survey	52 5900 117 2100	52 3600 118 200	83C14W	Whitehorse Creek
9	Alberta Geological Survey	52 5850 117 1950	52 4100 117 5000	93C14W	McLeod River
10	Alberta Geological Survey	52 5875 117 1975	52 3900 117 4600	83C14W	McLeod River
11	Alberta Geological Survey	52 5875 117 1975	52 3900 117 4600	83C14W	McLeod River
12	Alberta Geological Survey	52 5775 117 2000	52 3900 117 5100	83C14W	McLeod River-South
13	Alberta Geological Survey	52 5875 117 2275	52 4200 117 5400	83C14W	Whitehorse Creek
14	Alberta Geological Survey	52 5950 117 1950	52 3800 117 4000	83C13E	Cadomin Quarry
15	Alberta Geological Survey	52 175 116 550	51 3800 116 5800	83C1E	Hummingbird Creek-South
16	Alberta Geological Survey	52 200 116 520	51 3700 116 5000	83C1E	Hummingbied Creek-South
17	Hudson Bay Oil and Gas-1966	52 325 116 1375	51 3700 117 100	83C1E	Ram Range
18	Hudson Bay Oil and Gas-1966	52 1325 116 1500	51 4100 117 100	83C1E	First Ram Range
19	Alberta Geological Survey	52 1325 116 3100	51 4400 117 2100	83C2E	Goat Creek-Headwaters
20	Hudson Bay Oil and Gas-1966	52 1475 116 2725	51 4500 117 2400	83C1W	First Range
21	Alberta Geological Survey	52 380 116 2525	51 2900 117 2900	83C1W	Two O'Clock Creek
22	Alberta Geological Survey	52 428 116 2610	51 3500 117 3700	83C1W	Two O'Clock Creek
23	Alberta Geological Survey	52 2950 116 25	52 2000 116 1900	83C8E	Nordegg
24	Alberta Geological Survey	52 2950 116 125	52 1700 116 1500	83C8E	Nordegg
25	Alberta Geological Survey	52 3517 116 3515	52 1900 117 800	83C10E	Blackstone River-West
26	Alberta Geological Survey	52 3525 116 3525	52 1800 117 700	83C10E	Black Stone River-North
27	Alberta Geological Survey	52 3520 116 3500	52 1800 117 600	83C10E	Blackstone River-East
28	Frebold-1957	52 3975 116 4100	52 2300 117 1100	83C10E	Chungo Creek Gap
29	Hudson Bay Oil and Gas-1966	52 5625 117 475	52 3700 117 3700	83C14E	Red Cap Mountain

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
30	Alberta Geological Survey	52 2966 116 2700	52 1300 117 100	83C9W	Bighorn Range
31	Alberta Geological Survey	52 2775 116 2175	52 1100 116 5300	83C08W	Bighorn Range-South
32	Alberta Geological Survey	52 2775 116 2150	52 1000 116 5500	83C8W	Wapiabi Gap
33	Alberta Geological Survey	52 3000 116 2633	52 1200 117	83C8W	Wapiabi Gap
34	Alberta Geological Survey	52 3400 116 3400	52 1600 117 500	83C10E	Smith Creek
35	Alberta Geological Survey	52 1625 116 3333	51 5500 117 1400	83C7E	Goat Creek-Headwaters
36	Alberta Geological Survey	52 1975 116 3900	51 5200 117 3100	83C7E	Bighorn River-Headwaters
37	Alberta Geological Survey	52 2700 116 4800	51 5500 117 3600	83C7W	Job Creek
38	Alberta Geological Survey	52 2650 116 4550	52 300 117 2600	83C7W	Job Creek-North Fork
39	Alberta Geological Survey	52 25 116 1800	51 2700 117 2000	83C1W	Siffleur River Ridge
40	Alberta Geological Survey	52 1350 116 1525	51 5500 117 200	83C01W	Crooked Creek-Headwaters
41	Alberta Geological Survey	52 300 116 1700	51 3700 117 1300	83C1W	Whiterabbit Creek Ridge
42	Alberta Geological Survey	52 600 116 1875	51 3900 117 1400	83C1W	Whiterabbit Creek-North
43	Alberta Geological Survey	52 1075 116 3200	51 4000 117 4200	83C2E	Coral Creek Mouth
44	Alberta Geological Survey	52 675 116 2850	51 3300 117 3000	83C1W	Elliot Peak South
45	Alberta Geological Survey	52 700 116 2850	51 2400 117 4300	83C1W	Elliot Peak-South.
46	Alberta Geological Survey	52 833 116 350	51 4300 116 4000	83C1E	Onion Creek-Ram Range
47	Alberta Geological Survey	52 1000 116 1050	51 4800 116 5600	83C1E	North Ram River
48	Alberta Geological Survey	52 1100 116 1700	51 5200 117 200	83C1W	Ram Range-North
49	Alberta Geological Survey	52 1100 116 1700	51 5200 117 200	83C1W	North Fork-North Ram River
50	Alberta Geological Survey	52 1375 116 3425	51 3800 117 3700	83C2E	Mt. Stelfox
51	Alberta Geological Survey	52 1600 116 4075	51 3600 117 5600	83C7E	Coral Creek-Headwaters
52	Alberta Geological Survey	52 1550 116 4150	51 3100 117 5200	83C7E	Coral Creek-West Ridge
53	Alberta Geological Survey	52 2225 116 5600	51 3500 118 600	83C7W	Mt. McDonald
54	Alberta Geological Survey	52 2275 116 5375	51 3800 118 600	83C7W	Obstruction Mountain
55	Alberta Geological Survey	52 5900 117 4000	52 3500 118 2100	83C13E	Rocky River-Jacques Lake
56	Alberta Geological Survey	52 5366 117 2933	52 3000 118 1000	83C13E	Deception Mountain-Rocky
57	Alberta Geological Survey	52 5333 117 2933	52 2700 118 700	83C13E	Blackface Mountain
58	Alberta Geological Survey	52 5000 117 2200	52 2500 117 5900	83C14W	Medicine Tent River
59	Alberta Geological Survey	52 5050 117 2066	52 2500 118	83C14W	Deception Mountain Pass

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
60	Alberta Geological Survey	52 5000 117 2200	52 2500 118	83C14W	Deception Creek
61	Alberta Geological Survey	52 5000 117 2200	52 2500 118	83C14W	Deception Mountain
62	Alberta Geological Survey	52 4633 117 2617	52 1000 118 1400	83C14W	Rocky River-Headwaters
63	Alberta Geological Survey	52 4700 117 2800	52 1200 118 1900	83C14W	Alpland Creek-Headwaters
64	Alberta Geological Survey	52 4325 117 0750	52 2000 117 5000	83C11E	Southesk Pass
65	Alberta Geological Survey	52 4375 117 1000	52 1800 117 4800	83C11E	Southesk Cairn
66	Alberta Geological Survey	52 3500 117 400	52 100 117 4700	83C11E	Southesk River
67	Alberta Geological Survey	52 3666 117 400	52 1200 117 4600	83C11E	Mt. Southesk
68	Alberta Geological Survey	52 3775 117 0	52 1400 117 4000	83C11E	Mt. Dalhousie
69	Alberta Geological Survey	52 3775 117 50	52 1400 117 4000	83C11E	Southesk River-East
70	Alberta Geological Survey	52 3775 117 50	52 1400 117 4000	83C11E	Mt. Dalhousie
71	Alberta Geological Survey	52 1400 116 2725	51 4700 117 2700	83C1W	Highway 11-Roadcut
72	Alberta Geological Survey	52 1350 117 1000	51 1700 119 300	83C3E	Sunwapta Pass
73	Alberta Geological Survey	52 2650 116 1975	52 900 116 5000	83C8W	Bighorn Range-Southend
74	Alberta Geological Survey	52 3225 116 5025	52 1100 117 3500	83C10W	Opabin Creek-East
75	Alberta Geological Survey	52 3225 116 5175	52 1000 117 3500	83C10W	Opabin Creek-West
76	Alberta Geological Survey	52 5000 117 4200	52 200 118 5100	83C13E	Medicine Lake
77	Alberta Geological Survey	52 4700 117 4050	52 400 118 4100	83C13E	Maligne River
78	Alberta Geological Survey	52 4675 117 4050	51 5900 118 5000	83C13E	Maligne River
79	Hudson Bay Oil and Gas-1966	52 1900 116 3900	51 5200 117 3300	83C7E	Bighorn River-Headwaters
80	Hudson Bay Oil and Gas-1966	52 1650 116 3400	51 4700 117 2900	83C7E	Littlehorn Creek-Headwaters
81	Telfer-1933	52 5675 117 5750	52 700 119 400	83C13W	Grisette Mountain
82	Hudson Bay Oil and Gas-1966	52 1500 116 3200	51 4800 117 2600	83C2E	Whitegoat Creek
83	Gibson-1974	52 2800 117 200	51 3900 118 1200	83C7W	Mt. Olympus
84	Gibson-1968a	52 4700 117 3300	51 5800 118 4200	83C14W	Helmet Mountain
85	Gibson-1968a	52 5050 117 2250	52 2500 118	83C14W	Deception Mountain
86	Gibson-1968a	52 4400 117 800	52 1900 117 4800	83C11E	Mt. McBeath
87	Gibson-1968a	53 0 117 4300	52 3400 118 2000	83C13E	Rocky River
88	Mcgugan and Rapson-various	52 2725 116 5725	51 5400 118	83C07W	Arete Mountain
89	Gibson-1968a	53 0 118 0	52 1800 118 5700	83C13W	Colin Range-North

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SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
90	Mcgugan and Rapson-various	52 2900 116 5400	52 100 117 4700	83C07W	Valley Head Mountain
91	Alberta Geological Survey	53 2825 118 1625	53 2100 118 3000	83E08W	Wildhay River
92	Alberta Geological Survey	53 2825 118 1625	53 2100 118 3000	83E08W	Wildhay River
93	Alberta Geological Survey	53 2850 118 1675	53 2100 118 3000	83E8W	Rock Lake
94	Alberta Geological Survey	53 2950 118 1050	53 2400 118 2000	83E8E	Hoff Range-Wildhay River
95	Alberta Geological Survey	53 3900 118 3800	53 2500 118 5400	83E10E	Berland Range-North
96	Alberta Geological Survey	53 4750 119 2900	53 2000 120 300	83E14W	Muddywater River
97	Alberta Geological Survey	53 4775 119 3000	53 2000 120 600	83E14W	Llama Mountain
98	Alberta Geological Survey	53 4900 119 2900	53 2000 120 600	83E14W	Llama Mountain
99	Gibson-1967	53 4900 119 2900	53 2000 120 600	83E14W	Llama Mountain
100	Alberta Geological Survey	53 5275 119 5650	53 1300 120 3600	83E13W	Mt. Cote
101	Alberta Geological Survey	53 5625 119 5975	53 3100 120 3000	83E13W	Cote Creek-Headwaters
102	Alberta Geological Survey	53 4550 119 3125	53 1000 120 800	83E13E	Muddywater River Ridge
103	Alberta Geological Survey	53 4500 119 3200	53 800 120 1400	83E13E	Muddywater River Ridge
104	Alberta Geological Survey	53 4350 118 3500	53 4000 118 3900	83E10E	Adams Lookout
105	Alberta Geological Survey	53 4475 118 3733	53 4100 118 4200	83E10E	Adams Lookout
106	Alberta Geological Survey	53 3400 118 2900	53 2200 118 4600	83E9W	Minny Ridge
107	Alberta Geological Survey	53 3250 118 2400	53 2200 118 4400	83E9W	Zebra Mountain
108	Alberta Geological Survey	53 3250 118 2400	53 2200 118 4600	83E9W	Zebra Mountain
109	Alberta Geological Survey	53 3050 118 2000	53 1900 118 4000	83E9W	Shrew Creek
110	Alberta Geological Survey	53 3100 118 2050	53 1900 118 3700	83E9W	Seep Creek-Headwaters
111	Alberta Geological Survey	53 3125 118 1250	53 2300 118 2600	83E9W	Collie Creek-Headwaters
112		53 4300 118 5875	53 2300 119 2100	83E10W	Lancaster Creek
113	Alberta Geological Survey	53 3275 118 5433	53 200 119 3700	83E10W	Monoghan Creek-South Ridge
114	Alberta Geological Survey	53 3225 118 5500	53 200 119 3800	83E10W	Monoghan Creek Ridge
115	Alberta Geological Survey	53 3275 118 5425	53 200 119 3700	83E10W	Monoghan Creek Ridge
116	Alberta Geological Survey	53 3275 118 4200	53 600 119 1500	83E10E	South Berland-Headwaters
117	Alberta Geological Survey	53 3850 118 5633	53 1000 119 2900	83E10W	Rocky Pass
118	Alberta Geological Survey	53 3850 118 5625	53 1000 119 2900	83E10W	Rocky Pass Lake
119	Alberta Geological Survey	53 3850 118 5033	53 2000 119 1400	83E10W	Muskegg River-Headwaters

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
120	Alberta Geological Survey	53 3517 118 4850	53 600 119 2300	83E10W	North Berland River-Headwaters
121	Alberta Geological Survey	53 3750 118 3483	53 2700 118 4900	83E10E	Planet Creek Headwaters
122	Alberta Geological Survey	53 500 118 125	52 3800 118 4400	83E1E	Talbot Lake
123	Alberta Geological Survey	53 950 118 200	52 4700 118 4000	83E1E	Snake Indian River Bridge
124	Alberta Geological Survey	53 1450 118 1100	52 5100 118 4700	83E1E	Shale Banks
125	Alberta Geological Survey	53 1500 118 950	52 4800 118 5200	83E8E	Shale Banks-Creek East
126	Alberta Geological Survey	53 1550 118 925	52 5000 118 4700	83E8E	Shale Banks Creek
127	Walasko-1962	53 975 118 1675	52 3600 119 600	83E01W	Mt. Thornton
128	Alberta Geological Survey	53 300 118 400	52 3200 118 4700	83E1E	Morro Peak
129	Alberta Geological Survey	53 275 118 400	52 3200 118 4700	83E1E	Morro Peak
130	Alberta Geological Survey	53 450 118 875	52 3200 119	83E1E	Esplande Mountain
131	Alberta Geological Survey	53 1750 118 1625	52 5300 118 5100	83E8W	Snake Indian Falls
132	Alberta Geological Survey	53 2133 118 950	52 5900 118 4800	83E8E	Bosche Range-North
133	Alberta Geological Survey	53 2350 118 1350	52 5900 118 5100	83E8E	Bosche Range-North
134	Alberta Geological Survey	53 2380 118 1450	53 118 5000	83E8E	South Rock Lake
135	Alberta Geological Survey	53 2350 118 1350	52 5900 118 5100	83E8E	Bosche Range-North
136	Alberta Geological Survey	53 2050 118 3375	52 4900 119 1600	83E7E	Mt. Kelsey
137	Alberta Geological Survey	53 2050 118 3575	52 5000 119 1800	83E7E	Mt. Kelsey
138	Alberta Geological Survey	53 2725 118 2800	53 119 400	83E7E	Daybreak Peak
139	Alberta Geological Survey	53 2725 118 2800	53 119 400	83E7E	Daybreak Pass
140	Alberta Geological Survey	53 2217 118 280	53 1200 118 1800	83E8E	Mt. Kephala
141	Alberta Geological Survey	53 2250 118 150	53 1400 118 1500	83E8E	Mt. Kephala
142	Alberta Geological Survey	53 2400 118 250	53 1700 118 1600	83E8E	Soloman Creek
143	Alberta Geological Survey	53 2400 118 250	53 1700 118 1500	83E8E	Soloman Creek
144	Alberta Geological Survey	53 2750 118 800	53 2100 118 2200	83E8E	Wildhay River-South Fork
145	Alberta Geological Survey	53 2750 118 800	53 2000 118 2000	83E8E	South Tributary-Wildhay R.
146	Alberta Geological Survey	53 2575 118 4375	52 5400 119 2800	83E7E	Vega Peak
147	Alberta Geological Survey	53 2550 118 4400	52 5400 119 2800	83E7E	Vega Peak
148	Alberta Geological Survey	53 2875 118 5450	52 5500 119 4400	83E7W	Mt. Perce
149	Alberta Geological Survey	53 2825 118 5475	52 5500 119 4500	83E7W	Sunset Peak

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
150	Alberta Geological Survey	53 3000 118 3533	53 200 119 800	83E7E	Persimmon Range-South
151	Alberta Geological Survey	53 2425 118 3125	52 5700 119 600	83E7E	Mowitch Creek Cabin
152	Alberta Geological Survey	53 2500 118 2950	52 5800 119 300	83E8W	Mowitch Creek-Mouth
153	Alberta Geological Survey	53 2525 118 3675	52 5400 119 1600	83E7E	Mowitch Creek
154	Alberta Geological Survey	53 4400 119 2000	53 1500 119 5200	83E11W	Wolverine Creek Ridge
155	Alberta Geological Survey	53 4425 119 1850	53 1600 119 5200	83E11W	Wolverine Creek
156	Alberta Geological Survey	53 3775 119 950	53 119 4900	83E11W	Kvass Creek Headwaters
157	Alberta Geological Survey	53 3550 119 650	52 5900 119 4800	83E11E	Hardscramble Creek
158	Alberta Geological Survey	53 3625 119 50	53 400 119 3900	83E11E	Monoghan Creek-North Ridge
159	Alberta Geological Survey	53 3775 119 750	53 600 119 4600	83E11W	Kvass Creek-South
160	Alberta Geological Survey	53 2550 118 4250	52 5400 119 2300	83E7E	Vega Peak
161	Hudson Bay Oil and Gas-1966	53 2600 118 400	53 1900 118 1500	83E8E	North Tributary-Wildhay R.
162	Hudson Bay Oil and Gas-1966	53 3250 118 1500	53 3000 118 1900	83E9E	Collie Creek-Headwaters
163	Hudson Bay Oil and Gas-1966	53 3650 118 3250	53 2300 118 4900	83E10E	Planet Creek
164	Gibson-1967	53 3250 119 50	52 5900 119 4800	83E11E	Monoghan Creek
165	Gibson-1967	53 3550 118 5600	53 400 119 3600	83E10W	Sulphur River
166	Gibson-1967	53 2675 118 4600	52 5800 119 2800	83E7W	Sulphur River-Headwaters
167	Gibson-1967	53 3925 118 5900	53 1000 119 3000	83E10W	Rocky Pass
168	Alberta Geological Survey	53 3400 118 5000	53 500 119 2300	83E10W	South Sulphur River Cabin
169	Alberta Geological Survey	53 4175 119 1200	53 1400 119 4500	83E11E	Kvass Creek-North
170	Gibson-1967	53 3100 118 4300	53 200 119 1200	83E10E	South Berland River-Headw
171	Gibson-1967	53 3300 118 1800	53 2600 118 2900	83E9W	Mumm Creek-Headwaters
172	Gibson-1967	53 3500 119 800	52 5800 119 5200	83E11E	Hardscramble Creek
173	Gibson-1967	53 3800 119 700	53 600 119 4600	83E11E	Kvass Creek-South
174	Gibson-1967	53 700 118 600	52 3900 118 5400	83E1E	Greenock Mountain
175	Gibson-1964	53 2250 118 1250	52 5900 118 5000	83E8E	Moosehorn Creek Lake
176	Gibson-1964	53 3200 118 2100	53 2000 118 3800	83E9W	Seep Creek-East Fork
177	Alberta Geological Survey	53 2950 118 1075	53 2200 118 2400	83E8E	Mumm Creek
178	Alberta Geological Survey	53 2000 117 5600	53 1200 118 900	83F5W	Oldhouse Creek
179	Alberta Geological Survey	53 2100 117 5850	53 1500 118 900	83F5W	West Fork-Soloman Creek

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
180	Alberta Geological Survey	53 1425 117 4725	53 700 118	83F 4W	Folding Mountain
181	Alberta Geological Survey	53 1375 117 4650	53 600 117 5900	83F 4W	Drystone Creek
182	Telfer-1933	53 250 117 2675	52 4800 117 5200	83F 3W	Luscar Mountain
183	Frebold-1957	53 1050 117 5100	52 5800 118 900	83F 4W	Fiddle River
184	Alberta Geological Survey	53 2025 117 5925	53 1200 118 900	83F05W	Boule Roche
185	Alberta Geological Survey	53 1975 117 5750	53 1000 118 1500	83F05W	Boule Roche
186	Telfer-1933	53 1150 117 5250	52 5400 118 2100	83F04W	Pocahontas
187	Telfer-1933	53 225 117 2550	52 4500 117 5900	83F03W	Luscar Mountain
188	Alberta Geological Survey	53 375 117 5950	52 3600 118 4000	83F 4W	Emir Mountain
189	Alberta Geological Survey	53 1075 117 5025	52 5600 118 800	83F 4W	Fiddle River
190	Alberta Geological Survey	53 925 117 4800	52 5600 118 800	83F 4W	Fiddle River-South
191	Alberta Geological Survey	49 3725 114 3850	49 3100 115 4700	82G10E	Highway 3-Roadcut
192	Alberta Geological Survey	49 5900 114 2300	49 5000 115 1400	82G16W	White Creek
193	Alberta Geological Survey	49 5900 114 2300	49 5000 115 1500	82G16W	White Creek
194	Douglass-1958	49 5900 114 2300	49 5100 115 1300	82G16W	White Creek
195	Alberta Geological Survey	49 5175 114 2100	49 4400 115 1100	82G16W	Oldman River Gap
196	Alberta Geological Survey	49 5175 114 2100	49 4400 115 1200	82G16W	Oldman River Gap
197	Alberta Geological Survey	49 4475 114 2250	49 3600 115 1300	82G9W	Daisy Creek Summit
198	Alberta Geological Survey	49 4475 114 2200	49 3700 115 1300	83G9W	Daisy Creek Summit
199	Western Warner Oil-1965	49 4400 114 3800	49 4200 115 4800	82G10E	Allison Peak
200	Alberta Geological Survey	49 5175 114 4000	49 4700 115 4700	82G15E	Racehorse Creek-Summit
201	Alberta Geological Survey	49 3725 114 2050	49 3000 115 1400	82G9W	Rock Creek Summit
202	Alberta Geological Survey	49 3725 114 2050	49 2800 115 1100	82G9W	Rock Creek Summit
203	Western Warner Oil-1965	49 4250 114 3450	49 3900 115 4300	82G10E	Crowsnest Mountain
204	Western Warner Oil-1965	49 5650 114 4100	49 5400 115 5100	82G10E	Tornado Pass
205	Alberta Geological Survey	49 3975 114 4200	49 3500 115 5200	82G10E	Crow Mine
206	Alberta Geological Survey	49 3750 114 4150	49 3400 115 5200	82G10E	Crowsnest Pass
207	Kenny-1977	49 3250 115 1100	49 3400 117 2300	82G6W	Lizard Creek
208	Telfer-1933	49 2200 114 4200	49 1100 115 4800	82G7E	Flathead River
209	Western Warner Oil-1965	49 3350 114 3450	49 2800 115 4300	82G10E	Mt. Ptolemy
210	Alberta Geological Survey	49 3400 114 4000	49 2300 115 4900	82G10E	Tent Mountain

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
211	Alberta Geological Survey	49 3400 114 4000	49 2300 115 4900	82G10E	Tent Mountain
212	Western Warner Oil-1965	49 4250 114 3825	49 3900 115 4800	82G10E	Deadman Pass
213	Alberta Geological Survey	49 2900 114 2450	49 2000 115 1600	82G8W	Adanac Mine
214	Telfer-1933	49 3950 114 3825	49 3400 115 4700	82G10E	Phillips Pass
215	Alberta Geological Survey	49 4025 114 2500	49 3200 115 1600	82G9W	Grassy Mountain
216	Alberta Geological Survey	49 3725 114 4150	49 3300 115 5000	82G10E	Crowsnest Pass
217	Alberta Geological Survey	49 2950 114 2450	49 2000 115 1500	82G8W	Adanac Mine
218	Alberta Geological Survey	49 2775 114 4200	49 2100 115 5000	82G7E	Barnes Lake
219	Alberta Geological Survey	49 1825 114 5775	49 200 116 200	82G7E	Mt. Broadwood
220	Alberta Geological Survey	49 1900 114 5550	49 600 116	82G7E	Lodgepole Creek
221	Alberta Geological Survey	49 1800 114 5675	49 300 116 300	82G7E	Mt. Broadwood
222	Alberta Geological Survey	49 2775 114 4150	49 600 116 4100	82G7E	Flathead Pass
223	Alberta Geological Survey	49 5450 114 5075	49 4900 116	82G15W	Fording River
224	Alberta Geological Survey	49 3925 114 4400	49 3500 115 5300	82G10E	Highway 3-Roadcut
225	Alberta Geological Survey	49 5450 114 4075	49 5100 115 5000	82G15E	Mt. Erris
226	Alberta Geological Survey	49 4675 114 3800	49 4500 115 4700	82G15E	Racehorse Pass
227	Telfer-1933	49 3125 114 3950	49 800 116 3800	82G10E	Corbin
228	Alberta Geological Survey	49 2800 114 3550	49 1800 115 4200	82G7E	Flathead Range-South
229	Kenny-1977	49 2800 115 700	49 200 117 1000	82G6E	Lizard Range
230	Kenny-1977	49 5225 114 5625	49 4800 116 5900	82G15W	Brule Creek
231	Kenny-1977	49 5700 114 5800	49 5200 117 100	82G15W	Weight Creek
232	Telfer-1933	49 3775 114 5675	49 3800 116 5100	82G10W	Mt. Hosmer
233	Mcgugan and Rapson-various	49 4600 115 275	49 4000 117 10	82G14E	Cummings Creek
234	Mcgugan and Rapson-various	49 4875 114 4100	49 2600 116 3600	82G15E	Alexander Creek-Headwaters
235	Mcgugan and Rapson-various	49 5500 114 5075	49 5400 116 5400	82G15W	Fording River
236	Mcgugan and Rapson-various	49 3250 115 1100	49 1100 117 1600	82G11E	Lizard Creek
237	Gibson-1968b	49 5125 114 4675	49 4725 116 5300	82G15W	Mt. Salter
238	Gibson-1968b	49 4775 114 5950	49 4000 117 525	82G15W	Cummings Creek
239	Gibson-1968b	49 1475 114 5400	49 115 5400	82G2W	Lodgepole Creek-South

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
240	Alberta Geological Survey	50 4300 115 600	50 2500 116 1000	82J11E	King Creek
241	Alberta Geological Survey	50 4050 115 500	50 2200 116 800	82J11E	Elpoca Mountain
242	Mobil Oil-1965	50 4700 115 1600	50 2300 116 2900	82J14W	Mt Chester
243	Alberta Geological Survey	50 5600 115 900	50 4100 116 500	82J14E	Ribbon Creek
244	Hudson Bay Oil and Gas-1966	50 3200 114 4900	50 1600 115 3500	82J10W	Highwood Range
245	Alberta Geological Survey	50 3850 115 150	50 2700 115 5200	82J11E	Elpoca Mountain
246	Hudson Bay Oil and Gas-1966	50 3400 114 5000	50 1800 115 3900	82J10W	Gibralter Mountain
247	Alberta Geological Survey	50 3850 115 150	50 2000 116 200	82J11E	Elpoca Mountain Gap
248	Alberta Geological Survey	50 3850 115 150	50 1600 116	82J11E	Elpoca Mountain Group
249	Hudson Bay Oil and Gas-1966	50 3600 115 300	50 1500 116 700	82J11E	Elk Range Fire Tower
250	Alberta Geological Survey	50 5400 115 2000	50 2800 116 3200	82J14W	Spray Lake
251	Hudson Bay Oil and Gas-1966	50 4600 115 700	50 2300 116 300	82J14E	Mt. Evans-Thomas Creek
252	Alberta Geological Survey	50 4425 115 750	50 2700 116 1100	82J11E	Walker Creek
253	Hudson Bay Oil and Gas-1966	50 650 114 4300	50 300 115 5200	82J2E	Mt. Lyall
254	Alberta Geological Survey	50 3975 115 450	50 2000 116 800	82J11E	Whiteman Creek
255	Hudson Bay Oil and Gas-1966	50 4825 114 5350	50 3400 115 4300	82J15W	Nihahi Ridge-South
256	Alberta Geological Survey	50 750 114 2275	50 100 115 1600	82J1W	Mt. Livingstone
257	Hudson Bay Oil and Gas-1966	50 475 114 2000	49 5500 115 1200	82J1W	Livingstone Range
258	Hudson Bay Oil and Gas-1966	50 1000 114 2450	50 300 115 1800	82J1W	Mt. Livingstone-North
259	Norris-1965	50 2350 114 3675	50 900 115 2600	82J07E	Mt. Head Ranger Station
260	Hudson Bay Oil and Gas-1966	50 1950 114 3275	50 1200 115 2500	82J7E	Mt. Burke
261	Kenny-1977	50 2000 114 5700	49 5300 116 4500	82J7W	Mt. Bleasdell
262	Hudson Bay Oil and Gas-1966	50 4725 114 5000	50 3700 115 2100	82J15W	Forgetmenot Mountain
263	Alberta Geological Survey	50 900 114 2950	50 100 115 2200	82J1W	Savanna Creek
264	Alberta Geological Survey	50 925 114 2950	49 5500 115 1900	82J2E	Savanna Creek
265	Alberta Geological Survey	50 1075 114 2650	49 5700 115 1600	82J1W	Mt. Livingstone
266	Norris-1965	50 1375 114 3125	50 115 2000	82J02E	Plateau Mountain
267	Alberta Geological Survey	50 1750 114 3450	50 300 115 2400	82J7E	Cataract Creek
268	Douglass-1958	50 3300 114 3500	50 1900 115 2700	82J10E	Sullivan Creek Headwaters
269	Hudson Bay Oil and Gas-1966	50 5000 115 1300	50 2700 116 1500	82J14E	Fortress Mountain Ski Hill

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
270	Alberta Geological Survey	50 2800 114 3500	50 1800 115 500	82J7E	Trap Creek
271	Alberta Geological Survey	50 2850 114 3850	50 1400 115 2700	82J7E	Trapp Creek
272	Douglass-1958	50 3000 114 4100	50 1600 115 3200	82J7E	Puriform Mountain
273	Alberta Geological Survey	50 4300 114 4350	50 3300 115 1300	82J10E	Volcano Ridge
274	Alberta Geological Survey	50 3900 114 3550		82J10E	
275	Alberta Geological Survey	50 3575 114 5150	50 2100 115 4100	82J10W	Gibralter Mountain
276	Alberta Geological Survey	50 3575 114 5150	50 2100 115 4100	82J10W	Gibralter Mountain
277	Alberta Geological Survey	50 4300 114 5900	50 2700 115 3900	82J10W	Little Elbow River-Headwaters
278	Alberta Geological Survey	50 4300 114 5900	50 2400 115 5500	82J10W	Little Elbow River-Headwaters
279	Alberta Geological Survey	50 4150 114 5850	50 2600 115 4700	82J10W	Tombstone Mountain
280	Alberta Geological Survey	50 3600 114 4600	50 2200 115 3600	82J10W	Sheep River
281	Alberta Geological Survey	50 3375 114 5600	50 1400 115 5500	82J10W	Mist Mountain
282	Alberta Geological Survey	50 3325 114 5575	50 1400 115 5800	82J10W	Mist Mountain
283	Alberta Geological Survey	50 5425 114 4550	50 3900 115 2000	82J15W	Canyon Creek
284	Alberta Geological Survey	50 4750 114 5250		82J15W	
285	Alberta Geological Survey	50 5200 114 5600	50 3800 115 4500	82J15W	Nihahi Ridge-North
286	Alberta Geological Survey	50 5175 115 650	50 3700 115 5800	82J14E	Evans-Thomas Creek
287	Alberta Geological Survey	50 5175 115 625	50 3800 116 300	82J14E	Evans-Thomas Creek
288	Alberta Geological Survey	50 5200 115 600	50 3600 116	82J14E	Evan-Thomas Creek
289	Alberta Geological Survey	50 5150 115 1025	50 2900 116 800	82J14E	The Wedge
290	Alberta Geological Survey	50 5125 115 1450	50 3300 116 1500	82J14E	Mt. Kidd
291	Alberta Geological Survey	50 5075 115 1250	50 3450 116 1500	82J14E	Fortress Mountain
292	Alberta Geological Survey	50 4700 115 2050	50 700 117 300	82J14W	Mt. Burstall
293	Alberta Geological Survey	50 3900 115 1600	50 100 117	82J11W	Three Isle Lake
294	Alberta Geological Survey	50 4000 114 5900	50 2600 115 5700	82J10W	Mt. Rae
295	Alberta Geological Survey	50 4150 115 750	50 1300 116 1700	82J11E	Kananaskis River Canyon Camp
296	Alberta Geological Survey	50 5625 115 2400	50 3200 116 3500	82J14W	Goat Range
297	Alberta Geological Survey	50 5450 115 2600	50 3200 116 3900	82J14W	Mt. Turbulent
298	Harker and Mclarn-1958	50 5925 115 750	50 4300 116 400	82J14E	Mt. Lorette
299	Alberta Geological Survey	50 4000 115 475	50 2200 116 800	82J11E	Whiteman Creek

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
300	Gibson-1968b	50 1950 114 5675	49 5600 116 5200	82J7W	Mt. Bleasdell
301	Hudson Bay Oil and Gas-1966	50 3550 115 275	50 1500 116 800	82J11E	Elk Range Fire Tower
302	Hudson Bay Oil and Gas-1966	50 4500 115 650	50 2300 116 300	82J14E	Mt. Evans-Thomas
303	Mobil Oil-1965	50 5425 115 1675	50 3400 116 1900	82J14W	Mt. Bogart
304	Mobil Oil-1965	50 4925 115 1750	50 2500 116 2700	82J14W	Mt. Galatea
305	Mobil Oil-1965	50 4725 115 1550	50 2400 116 2600	82J14W	Mt. Chester
306	Hudson Bay Oil and Gas-1966	50 4500 115 1125	50 1700 116 2000	82J14E	Mt. Lawson
307	Hudson Bay Oil and Gas-1966	50 4450 115 1325	50 2000 116 2400	82J11E	Mt. Kent-North
308	Hudson Bay Oil and Gas-1966	50 4225 115 1075	50 1400 116 2000	82J11E	Mt. Kent-South
309	Mcgugan and Rapson-various	50 600 115 75	50 400 116 5200	82J03E	Mt. Peck
310	Norris-1965	50 450 114 4325	49 5300 115 5000	82J02E	Beehive Mountain
311	Mcgugan and Rapson-various	50 1700 115 300	50 1700 117	82J06E	Connor Lake
312	Mcgugan and Rapson-various	50 4700 115 975	50 2800 116 1300	82J14E	Highway 40-Roadcut
313	Mcgugan and Rapson-various	50 4075 115 150	50 2200 116 200	82J11E	Tombstone Mountain
314	Alberta Geological Survey	50 5600 115 900	50 4000 116 300	82J14E	Ribbon Creek
315	Alberta Geological Survey	50 900 114 4300	50 400 115 5400	82J2E	Mt. Gass
316	Frebold-1957	54 1200 119 4900		83L4W	Stinking Springs
317	Alberta Geological Survey	51 5350 116 1025	51 3700 116 5900	82N16E	Ram Falls-Headwaters
318	Alberta Geological Survey	51 5325 116 1025	51 3100 117 2700	82N16E	Ram River-Headwaters
319	Alberta Geological Survey	51 5200 116 900	51 3000 116 5900	82N16E	Whiterabbit Creek-Headwaters
320	Hudson Bay Oil and Gas-1966	51 5800 116 050	51 3600 116 4700	82N16E	Wampum Peak-North
321	Alberta Geological Survey	51 5875 116 950	51 3800 117 100	82N16E	Headwaters-Whiterabbit Cr.
322	Alberta Geological Survey	51 5875 116 0950	51 3500 116 5600	82N16E	Whiterabbit Creek-Headwat
323	Alberta Geological Survey	51 5566 116 700	51 2900 117 200	82N16E	Indian Lookout Pass
324	Alberta Geological Survey	51 5800 115 1500	51 5000 115 3600	82014E	Clearwater River
325	Hudson Bay Oil and Gas-1966	51 3825 115 3525	51 1600 116 2400	82012E	Dormer Mountain
326	Alberta Geological Survey	51 5400 115 2100	51 4700 115 4300	82014W	Limestone Mountain South
327	Alberta Geological Survey	51 4450 115 3250	51 3000 116 2200	82012E	Bighorn Creek Falls
328	Alberta Geological Survey	51 4450 115 3250	51 2800 116 2200	82012E	Bighorn Creek Falls
329	Hudson Bay Oil and Gas-1966	51 5175 115 3275	51 3100 116 1700	82013E	Limestone Creek-Headwater

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
330	Alberta Geological Survey	51 4400 115 2900	51 2600 116 1600	82012E	Eagle Creek
331	Hudson Bay Oil and Gas-1966	51 5775 115 5000	51 3700 116 3400	82013W	Washout Creek
332	Alberta Geological Survey	51 4400 115 2900	51 2600 116 1500	82011W	Eagle Creek
333	Telfer-1933	51 2850 115 4125	51 800 116 3400	8205E	Cuthead Creek-Headwaters
334	Alberta Geological Survey	51 4350 115 2700	51 2300 116 1200	82011W	James Pass
335	Alberta Geological Survey	51 3400 115 2600	51 1900 115 5900	82011W	Sheep Creek
336	Alberta Geological Survey	51 3400 115 2600	51 1975 116 75	82011W	Sheep Creek
337	Alberta Geological Survey	51 600 115 1900	50 4600 116 1400	8203W	Cougar Canyon
338	Telfer-1933	51 3600 115 4750	51 1400 116 4000	82012W	Snow Pass
339	Alberta Geological Survey	51 150 115 1500	50 4400 116 900	8203W	Pigeon Creek
340	Alberta Geological Survey	51 200 115 1500	50 4800 116 1200	8203W	Pigeon Creek
341	Alberta Geological Survey	51 550 115 1000	50 4800 115 5700	8203E	Type Section-Exshaw Formation
342	Alberta Geological Survey	51 4800 115 5200	51 2300 116 3800	82013W	Forbidden Creek
343	Alberta Geological Survey	51 4850 115 3050	51 3000 116 1700	82013E	Bighorn Creek-Headwaters
344	Alberta Geological Survey	51 5750 115 4650	51 3900 116 3500	82013W	Washout Creek-Headwaters
345	Alberta Geological Survey	51 1025 115 1325	50 5600 116 300	8203E	South Ghost River-Headwaters
346	Alberta Geological Survey	51 1325 115 1525	50 5700 116 400	8203W	South Ghost River-Headwaters
347	Alberta Geological Survey	51 1325 115 1525	50 5900 116 400	8203W	Saddle Peak
348	Alberta Geological Survey	51 1275 115 1375	50 5400 116 200	8203E	Saddle Peak
349	Alberta Geological Survey	51 413 115 2550	50 4200 116 2400	8203W	Mt. Rundle Gap
350	Alberta Geological Survey	51 1700 115 1850	51 200 116 900	8206W	Mt. Costigan
351	Alberta Geological Survey	51 1700 115 1850	51 200 116 900	8206W	Mt. Costigan
352	Alberta Geological Survey	51 1700 115 1850	51 325 116 725	8206W	Mt. Castigan
353	Alberta Geological Survey	51 2050 115 2850	51 300 116 2200	8206W	Mt. Aylmer
354	Douglass-1958	51 2050 115 2850	51 300 116 2000	8206W	Mt. Aylmer
355	Alberta Geological Survey	51 2300 115 2700	51 800 116 1900	8206W	Ghost River Headwaters
356	Alberta Geological Survey	51 2475 115 2725	51 500 116 2200	8206W	Mt. Oliver
357	Alberta Geological Survey	51 3525 115 2850	51 1500 116 2200	82011W	Otuskwan Ridge
358	Alberta Geological Survey	51 3550 115 2925	51 1800 116 1800	82012E	Otuskwan Ridge
359	Alberta Geological Survey	51 3550 115 2925	51 1800 116 1800	82012E	Otaskwan Ridge

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
360	Alberta Geological Survey	51 5550 115 2675	51 4800 115 4700	82014W	Limestone Mountain
361	Harker and Mclarn-1958	52 0 115 2850	51 4600 115 5500	82014W	Limestone Mountain
362	Alberta Geological Survey	51 875 115 3450	50 4400 116 4600	8204E	Sulphur Mountain
363	Alberta Geological Survey	51 800 115 4133	50 3000 117 2600	8204E	Brewster Creek
364	Alberta Geological Survey	51 300 115 3025	50 4600 116 2700	8204E	Sulphur River
365	Alberta Geological Survey	51 1600 115 4600	50 5000 116 5600	8205W	Mt. Ishbel
366	Alberta Geological Survey	51 1725 115 3200	51 116 2700	8205E	Cascade River Crossing
367	Alberta Geological Survey	51 2150 115 3900	51 100 116 3300	8205E	Vermilion Range
368	Alberta Geological Survey	51 2050 115 4150	50 5500 116 5400	8205E	East of Forty Mile Creek
369	Alberta Geological Survey	51 2175 115 3500	51 300 116 3000	8205E	Stoney Creek
370	Alberta Geological Survey	51 2475 115 5325	50 5000 117 4200	8205W	Badger Pass
371	Alberta Geological Survey	51 2450 115 4725	50 4700 117 3500	8205W	Flints Park Cabin
372	Alberta Geological Survey	51 2475 115 4850	50 4500 117 3600	8205W	Cascade River-Headwaters
373	Alberta Geological Survey	51 2450 115 4000	51 117 300	8205E	Cuthead Creek-South
374	Alberta Geological Survey	51 2550 115 3950	51 400 116 3200	8205E	Cuthead Creek-North
375	Alberta Geological Survey	51 3100 115 4325	51 1000 116 3400	82012E	Wigmore Creek
376	Alberta Geological Survey	51 2975 115 4850	51 400 117	8205W	Panther River-Headwaters
377	Alberta Geological Survey	51 3300 115 4350	51 1300 116 3700	82012E	Panther Mountain Gap
378	Alberta Geological Survey	51 3400 115 4300	51 1200 116 3400	82012E	Panther Mountain Gap
379	Alberta Geological Survey	51 4025 115 5825	51 1500 117 1000	82012W	McConnell Creek
380	Alberta Geological Survey	51 3650 115 4800	51 1600 116 4900	82012W	Snow Peak
381	Alberta Geological Survey	51 3925 115 5000	51 1900 116 4300	82012W	Mt. White
382	Alberta Geological Survey	51 4075 115 5000	51 2100 116 4300	82012W	Mt. Tyrrell
383	Alberta Geological Survey	51 4325 115 5425	51 2200 116 4500	82012W	Divide Creek
384	Alberta Geological Survey	51 3825 115 4175	51 1800 116 3000	82012E	Gable Mountain
385	Alberta Geological Survey	51 4550 115 5300	51 2900 116 4700	82013W	Forbidden Creek-Summit
386	Alberta Geological Survey	51 4575 115 5375	51 2300 116 4100	82013W	Forbidden Creek-Headwaters
387	Alberta Geological Survey	51 5400 115 5475	51 3500 116 4100	82013W	North of Peters Peak
388	Alberta Geological Survey	51 5450 115 5400	51 3800 116 4400	82013W	North of Mt. Peters
389	Alberta Geological Survey	51 5400 115 5475	51 3500 116 4100	82013W	North of Peters Peak

SECTION	REFERENCE	LATITUDE LONGTITUDE	PALINSPASTIC POSITION	NTS SHEET	SECTION NAME
390	Alberta Geological Survey	51 5700 115 4650	51 4200 116 3600	82013W	Washout Creek-Headwaters
391	Alberta Geological Survey	51 1000 115 1750	50 5400 116 1300	8203W	Mt. Stewart
392	Alberta Geological Survey	51 1000 115 1750	50 5400 116 1300	8203W	Mt. Stewart
393	Telfer-1933	51 3075 115 4775	51 1100 116 3800	82012W	Panther River-Headwaters
394	deschmidt-1916	51 850 115 3750	50 4400 116 4900	8204E	Sundance Canyon
395	Alberta Geological Survey	51 1375 115 3100	50 5800 116 2500	8203E	Lake Minnewanka Damsite
396	deschmidt-1916	51 1100 115 3675	50 4900 116 3500	8204E	Mt. Norquay
397	Mobil Oil-1965	51 3900 115 2725	51 2100 116 1400	82011W	Mouth of Dogrib Creek
398	Hudson Bay Oil and Gas-1966	51 4975 115 4100	51 3200 116 2800	82013E	Skelton Creek
399	Alberta Geological Survey	51 875 115 3333	50 4800 116 3200	8204E	Bow Falls
400	Alberta Geological Survey	51 1466 115 3066	50 5700 116 2500	8204E	Minnewanka Highway
401	Alberta Geological Survey	51 1425 115 3025	50 5700 116 2700	8204E	Lower Cascade River
402	Mcgugan and Rapson-various	51 5100 115 5900	51 3000 116 4900	82013W	Mt. Peters
403	Gibson-1974	51 700 115 3100	50 4700 116 3200	8204E	Sulfur Mountain
404	Alberta Geological Survey	51 5300 115 4050	51 3200 116 2400	82013E	Timber Creek
405	First Nuclear Corp.-1981	49 0500 114 3425		82G2E	Cabin Creek
406	First Nuclear Corp.-1981	49 0700 114 4150		82G2E	Cabin Creek-North
407	First Nuclear Corp.-1981	49 0700 114 4600		82G2E	Bighorn Creek
408	First Nuclear Corp.-1981	49 0750 114 4000		82G2E	Cabin Creek-West

Appendix 2. Thrust Sheets and Their Inferred Displacements (miles)

Livingston	40	Cripple Creek	30
Sullivan Creek	40	Brazeau	18
McConnell	40	Siffleur	88
Dyson Mountain	30	Pipestone Pass	106
Lewis	52	Balingard	50
Hosmer	103	Bare	45
Gypsum	100	Chetamon	74
Alexander	95	Solomon	5
Borgeau	88	Hoff	12
Sulphur Mountain	60	Tip Top	18
Sawback	60	Mt. Russell	27
Simpson Pass	124	Rocky Pass	40
Fatigue	106	Greenock	46
Rundle	50	Colin	52
Inglismolde	45	Snake Indian	84
Aylmer	44	Folding Mountain	12
Clearwater	43	Nikanassin	30
Burnt Timber	30	Miette	38
Bighorn	30	Rocky River	43

Appendix 3. Ranger Canyon Basal Phosphate Zone - Lithologic and Chemical Analysis Data

APPENDIX 3. Ranger Canyon Formation Basal Phosphate Zone - Lithologic and Chemical Analysis Data.

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	WEIGHTED VALUES VANADIUM (ppm)	WEIGHTED VALUES URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
21	Phos; cmt	0.20	22.60	100	60.9	4.52	2.26	1	K
35	Phos; nod,pell	0.45	15.51	60	11.3	6.98	3.49	2	J
38	Ss; pell	0.60	14.30	70	15.5	8.58	4.29	3	J
41	Cgl; nod,cmt	0.60	7.90	50	19.1	4.74	2.37	1	K
43	Cgl; cmt,nod	0.50	23.00	136	85.7	11.50	5.75	1	J
48	Cgl; pebls	0.10	21.10	80	16.3	2.11	1.05	1	K
53	Ss; cmt	0.65	3.78	40	14.8	2.46	1.23	1	M
62	Cgl; cmt	0.10	4.50	60	14.2	0.45	0.22	1	M
64	Cgl; pebls	0.40	28.30	240	44.9	11.32	5.66	1	J
66	Cgl; pebls	0.20	4.30	50	3.9	0.86	0.43	1	M
68	Cgl; pebls	0.20						1	
71	Cgl; cmt	0.15	2.53	60	7.1	0.38	0.19	1	M
75	Cgl; nod,cmt	1.00	7.68	80	16.6	7.68	3.84	1	J
77	Cgl; nod,cmt	0.70	11.90	80	39.1	8.33	4.16	1	J
81	Phos; nod	0.24						1	
90	Cgl;	0.20						1	
100	Ss; pell	0.40	4.60	180	34.5	1.84	0.92	2	M
102	Cgl; cmt	0.20	15.20	140	34.7	3.04	1.52	1	K
113	Cgl; cmt	0.50	3.40	70	8.7	1.70	0.85	1	M
122	Cgl; pebls,cmt	0.30	0.06	10	5.8	0.02	0.01	1	N
127	Cgl;	0.30						1	
128	Ss; pebls	0.35	14.85		63.0	5.20	2.60	1	K
146	Cgl; cmt	0.60	5.80	50		3.48	1.74	1	M
149	Cgl; cmt,pebls	0.10	11.10	100	47.2	1.11	0.55	1	K
151	Cgl; cmt	0.20	14.10	90	25.9	2.82	1.41	1	K
157	Cgl; cmt	1.00	3.80	30	15.9	3.80	1.90	1	M
158	Cgl; cmt	0.35	23.31	131	17.3	8.16	4.08	1	J
210	Cgl; cmt	1.50	17.10	120	77.5	17.10	12.82	1	F
232	Phos; cmt	0.27	24.59			6.64	3.32	1	J
236	Cgl; cmt	0.20						1	

240	Ss	0.15						1	
295	Ss; nod,cmt	0.40	22.60	210	112.0	9.04	4.52	1	J
301	Qzt; cmt	0.30						1	
304	Phos; 7	0.14	30.00			4.20	2.10	1	K
305	Ss; nod	0.91	16.57			15.08	7.54	3	G.H
317	Cgl; cmt	0.40	19.60	140		7.84	3.92	1	J
321	Cgl; cmt	0.25	2.48	52	6.6	0.62	0.31	1	M
337	Cgl;	2.00	2.20	60	10.6	2.20	2.20	1	L
342	Cgl; cmt,pebls	0.10	15.10	120	44.7	1.51	0.75	1	K
363	Cgl; cmt,pebls	0.20	8.60	40	12.9	1.72	0.86	1	K
365	Cgl; cmt	0.40						1	
366	Cgl; cmt	0.25	3.92	140	7.6	0.98	0.49	1	M
371	Phos	0.20	23.20	100	18.7	4.64	2.32	1	K
377	Cgl; cmt	0.25	4.00	20	8.6	1.00	0.50	1	M
379	Dol; cmt	1.00	7.60	180	18.8	7.60	3.80	1	J
381	Ss; pebls	1.50	1.91	53	6.0	1.91	1.43	4	L
389	Ss; nod	0.10	2.40	40	6.3	0.24	0.12	1	M
393	Cgl; nod	0.06	23.83			1.43	0.71	1	K
394	Sh; intbd	0.52	18.53			9.64	4.82	3	J
396	Ss; cmt,nod	0.61	3.83			2.34	1.17	1	M
399	Cgl; cmt	0.10	1.80	30	1.4	0.18	0.09	1	M
402	Cgl; cmt	0.30						1	

Appendix 4. Lithologic and Chemical Analysis Data - Ranger Canyon Upper Phosphate Zone

APPENDIX 4. Lithologic and Chemical Analysis Data - Ranger Canyon Upper Phosphate Zone (RCUP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*	CLASS
62	Cgl;phost	0.10	1.50	50	3.0	0.15	?	1	M
125	Cgl;cmt,nod	0.40	7.40	60	21.0	2.96	1.48	1	K
155	Cgl;pbls,cmt	0.40	3.40	30	14.7	1.36	0.68	1	M
210	Ss;cmt	0.50	1.40	120	13.8	0.70	0.35	1	M
229	Ss;nod	0.30	10.00			3.00	1.50	1	K
247	Cgl;nod,cmt	0.30	5.50	80	14.6	1.65	0.82	1	M
252	Cgl;nod	0.50	2.28	110	8.0	1.14	0.57	1	M
299	Ss;nod	1.00	1.70	60	8.3	1.70	0.85	2	M
301	Ss;nod	0.76						1	
304	Ss;nod	0.64	30.00?					1	
305	Ss;nod	0.70	28.70?					1	
306	Ss;nod	0.91						1	
307	Ss;nod	1.07						1	
308	Ss;nod	0.61						1	
309	Cgl;	0.30						1	
332	Cgl;pbls,cmt	0.10	1.50	40	5.0	0.15	0.07	1	M
359	Cgl;pbls,cmt	0.50	2.76	50	14.2	1.38	0.69	1	M
363	Phos	1.50	6.70	80	9.1	6.70	5.02	1	I, J
365	Cgl;pbls	0.10						1	
371	Cgl;cmt	0.20	0.35	20	1.5			1	M
377	Ss;pbls,nod	0.75	5.42	66	6.8	4.07	2.03	2	M
381	Ss;cmt	0.30	2.80	50		0.84	0.42	1	M
389	Ss;cmt	0.30	2.30	100	7.0	0.69	0.34	1	M
421•	Cgl;pbls	1.52						1	
97•	Cgl;pbls	0.70	4.55	100	20.0	3.19	1.59	1	M
116•	Cgl;cmt	0.20	19.40	80	27.0	3.88	1.94	1	K
117•	Cgl;cmt	1.00	3.69	98	6.3	3.69	1.84	2	M

? Assay based on nodules only.

• Sections of Mowitch Formation Basal Phosphate (MBP) - Equivalent to RCUP??

Appendix 5. Lithologic and Chemical Analysis Data - Basal Fernie Phosphate (BFP).

APPENDIX 5. Lithologic and Chemical Analysis Data - Basal Fernie Phosphate (BFP).

SECTION	LITHOLOGY	THICKNESS (m)	WEIGHTED VALUES P_2O_5 %	VANADIUM (ppm)	URANIUM (ppm)	P_2O_5 % (1 m.)	P_2O_5 % (2 m.)	N*	CLASS
5	Lst;phost	0.15						1	
6	Ls;phost	2.10						1	
19	Ss;pell	0.50	14.02	70	39.6	7.01	3.50	3	J
23	Cgl;nod	0.20	1.00	120	11.0	0.20	0.10	1	M
42	Phos;pell	0.80	9.30	140	55.7	7.44	3.72	1	J
93	Cgl;	0.15						1	
103	Ss;cmt,nod	0.15	14.13	100	36.0	2.12	1.06	1	K
112	Ss;phost	0.15						1	
114	Cgl;phost	0.30	2.13	80	29.3	0.64	0.32	2	M
123	Cgl;pbls	0.10	7.80	40	23.0	0.78	0.39	1	K
134	Cgl;cmt	0.85	0.84	871	31.6	0.72	0.36	3	M
137	Ss;cmt	0.60	11.50	60	43.8	6.90	3.45	1	J
152	Ss;pell	0.50	1.92	30	7.6	0.96	0.48	1	M
153	Ss;pell,cmt	0.10	7.00	50	13.0	0.70	0.35	1	K
159	Ss;phost,pell	1.20	1.65	45	6.0	1.65	0.99	3	L
182	Cgl;cmt	0.09	11.55			1.04	0.52	1	K
188	Cgl;pbls	0.50	3.94	438	61.4	1.97	0.98	2	M
190	Cgl;pell	0.02	5.00	150	120.0	0.10	0.05	1	M
193	Ss;pell	0.65	1.64	61	6.1	1.07	0.53	2	M
196	Ss;nod	0.70	0.82	40	5.5	0.58	0.29	1	M
197	Ss;nod,pell	0.40	3.55	30		1.42	0.71	1	M
405	Phos;pell	3.25	21.33	76	73.7	31.40$	29.73$	13	A,B
202	Ss;nod,pell	0.30	8.80	80	40.0	2.64	1.32	1	K
408	Phos;pell	2.75	11.95	163	38.4	19.29$	15.24$	11	E,F
205	Phos;pell	1.42	20.64			21.24$	14.65	4	E,F
207	Phos;pell	3.11	13.86			18.53$	13.86	5	E,F
208	Phos	1.10						1	
406	Phos;pell	2.00	16.41	162	49.9	20.49$	16.41	8	E,F
215	Cgl;phost	0.15						1	
407	Phos;pell	4.00	10.37	400	138.8	21.99$	15.99$	16	E,F
217	Ss;nod,cmt	2.20	2.92	300	38.8	2.92	2.92	2	M

218	Phos;pell	2.90	7.96	112	10.1	10.68$	7.96	8	H,J
220	Phos;pell	3.45	5.07	126	18.4	9.05$	5.07	6	J
223	Phos;pell	2.09	8.70	90	29.0	9.02$	8.70	7	J,H
224	Phos;pell	2.05	13.87	35	20.9	25.03$	13.87	6	C,F
254	Cgl;cmt,pbls	0.20	9.95	50	69.5	1.99	0.99	1	K
256	Sltst;Phost,nod	2.60	2.13			2.13	2.13	4	L+
257	Ss;nod	0.90						1	
258	Ss;nod	0.45						1	
261	Phos;pell	0.91	16.64			15.15	7.57	2	H,G
262	Ss;nod	9.14						2	
273	Ss	2.00	0.60	30	2.6	0.60	0.60	1	N
282	Ss;cmt,pell	1.10	3.30	32	21.9	3.30	1.81	2	L
283	Cgl;cmt	0.50	0.74	20		0.37	0.18	1	N
323	Sltst;pell	1.30						3	
324	Cgl;nod,cmt,pbls	0.05	16.20	60	78.0	0.81	0.40	1	K
327	Cgl;nod	0.60	2.90	160	38.8	1.74	0.87	1	M
333	Phos;pell	0.60	7.11			4.27	2.13	4	K
335	Ss;pell,cmt	0.30	4.20	60	19.6	1.26	0.63	1	M
338	Cgl;cmt	0.09	7.66			0.69	0.34	1	K
339	Cgl;	0.21	15.90			3.34	1.67	1	K
346	Ss	0.80						1	
367	Phos;pell	1.50	1.43	5	2.4	1.43	1.07	4	L
374	Phos;pell	0.75	17.61			13.21	6.60	4	G,H
375	Phos;pell	2.15	9.20	44	18.4	14.10$	9.20	6	G,H
385	Phos;pell	2.10	2.90	90	15.3	6.04$	2.90	2	J
400	Phos;pell	0.60	18.08			10.85	5.42	2	J

* Number of samples used to calculate P2O5 % column.

$ Values recalculated from original data, not based on P2O5 % column - see Appendix 1.

APPENDIX 6. Resource Estimate Calculations

Estimates of the amount of phosphate present within a given zone were made under the following conditions and assumptions.

1. All of these figures are NOT estimates of economically recoverable phosphate. None of these deposits are economically recoverable under present economic conditions.
2. These figures represent, first attempts to show how much phosphate is present in situ if it is decided that these low grade deposits are worth mining. The geological assumptions are based on an on strike and downdip continuity of phosphate beds with respect to grade and thickness, no structural complications i.e. thickening of pinching out of beds, and no regard for topographic setting. Further the "economic type" considerations are of no concern; regarding price expectations, technological costs, pollution control, tax charges, transportaton access and charges, marketability of product, availability of capital, manpower, and all other similar concerns.
3. "Gross t (300 m)" is based on the outcrop length (in kms) within a given area, times 1 or 2 m thickness - depending on Class description - times a 300 metres dipslope distance. 300 metres is considered to be a maximum amount by either open pit or underground methods.
4. "Gross t (50 m)" - same as in "Gross t (300 m)" except a more conservative estimate of 50 m of downdip ore is taken.
5. Classes J, G, E, C, and A deposits were based on 1 metre thickness and Classes H, F, D, and B on 2 metres. Some dilution of the original raw data was by necessity added to most "J" Class deposits to bring them up to at least a 1 metre thickness.
6. Specific gravity of phosphate rock was considered to be 12 cubic feet/ton or 0.33984 cubic metres/0.9078 t (Sheldon, 1963).

7. Example of Calculation

Outcrop Length (O.L.) = kilometres measured from map and rounded off to nearest whole number, (x1000 to yield metres)

Thickness (T) = 1 or 2 metres, depending on Class (Fig. 6)

Downdip length (D) = 300 or 50 metres

Volume (V) = O.L x T x D cubic/metres

$t = \underline{V} \times \underline{0.9078} / 0.33984$ t.

Appendix 7. Average Microprobe Composition of Phosphorites - This Study - By Petrographic Lithotype and Geological Period.

Appendix 7. Average Microprobe Compositions of Phosphorites - This Study - By Petrographic Lithotype and Geological Period.

	PETROGRAPHIC LITHOTYPES							GEOLOGICAL PERIOD					
	PELLETS[2] (n=20)[1]	BONES (n=5)	SHELLS (n=7)	INTRACLASTS (n=8)	PRIMARY CEMENT (n=9)	FRANCOLITE CEMENT (n=2)	FLUORAPATITE CEMENT (n=2)	LOWER JURASSIC (n=16)	DEV./MISS. (n=6)	TRIASSIC (n=7)	P€ (n=2)	PERMO-PENN (n=19)	MIDDLE JURASSIC (n=3)
F	4.147	4.343	3.494	3.955	4.273	4.346	4.315	4.079	3.367	4.168	4.315	4.277	3.998
Na_2O	0.439	0.816	0.580	0.397	0.482	0.825	0.074	0.333	0.517	0.959	0.074	0.540	0.224
MgO	0.731	0.474	0.837	0.649	0.575	0.629	0.649	0.698	0.815	0.658	0.649	0.558	1.070
Al_2O_3	0.734	0.292	1.385	1.339	0.555	0.429	0.351	0.925	0.1675	0.640	0.351	0.343	2.187
P_2O_5	35.574	36.842	32.619	33.484	37.477	37.713	40.565	33.532	33.734	36.947	40.565	36.764	36.181
S	0.816	0.728	0.460	0.589	0.5888	0.752	0.0	0.691	0.297	0.918	0.0	0.683	0.820
Cl	0.0	0.0	0.0	0.154	0.018	0.0	0.028	0.007	0.0	0.009	0.028	0.052	0.0
K_2O	0.123	0.021	0.607	0.379	0.139	0.071	0.033	0.218	0.750	0.145	0.033	0.074	0.277
CaO	49.987	51.885	44.675	48.386	51.653	51.677	54.883	48.034	44.644	51.319	54.883	51.615	50.292
TiO_2	0.052	0.0	0.055	0.180	0.032	0.0	0.0	0.111	0.0	0.086	0.0	0.015	0.166
V_2O_5	0.025	0.0	0.015	0.075	0.051	0.0	0.062	0.050	0.018	0.062	0.062	0.018	0.0
MnO	0.064	0.053	0.051	0.072	0.072	0.050	0.183	0.056	0.051	0.124	0.183	0.053	0.056
FeO[3]	1.186	0.103	2.327	1.082	0.523	0.122	0.055	1.009	3.344	0.194	0.055	0.474	2.519
ZnO	0.657	0.107	0.161	0.071	0.084	0.082	0.0	0.075	0.144	0.184	0.0	0.059	0.0

[1] n=number of samples

[2] For description of all lithotypes see Table 2.

[3] Total Fe assumed to be as FeO

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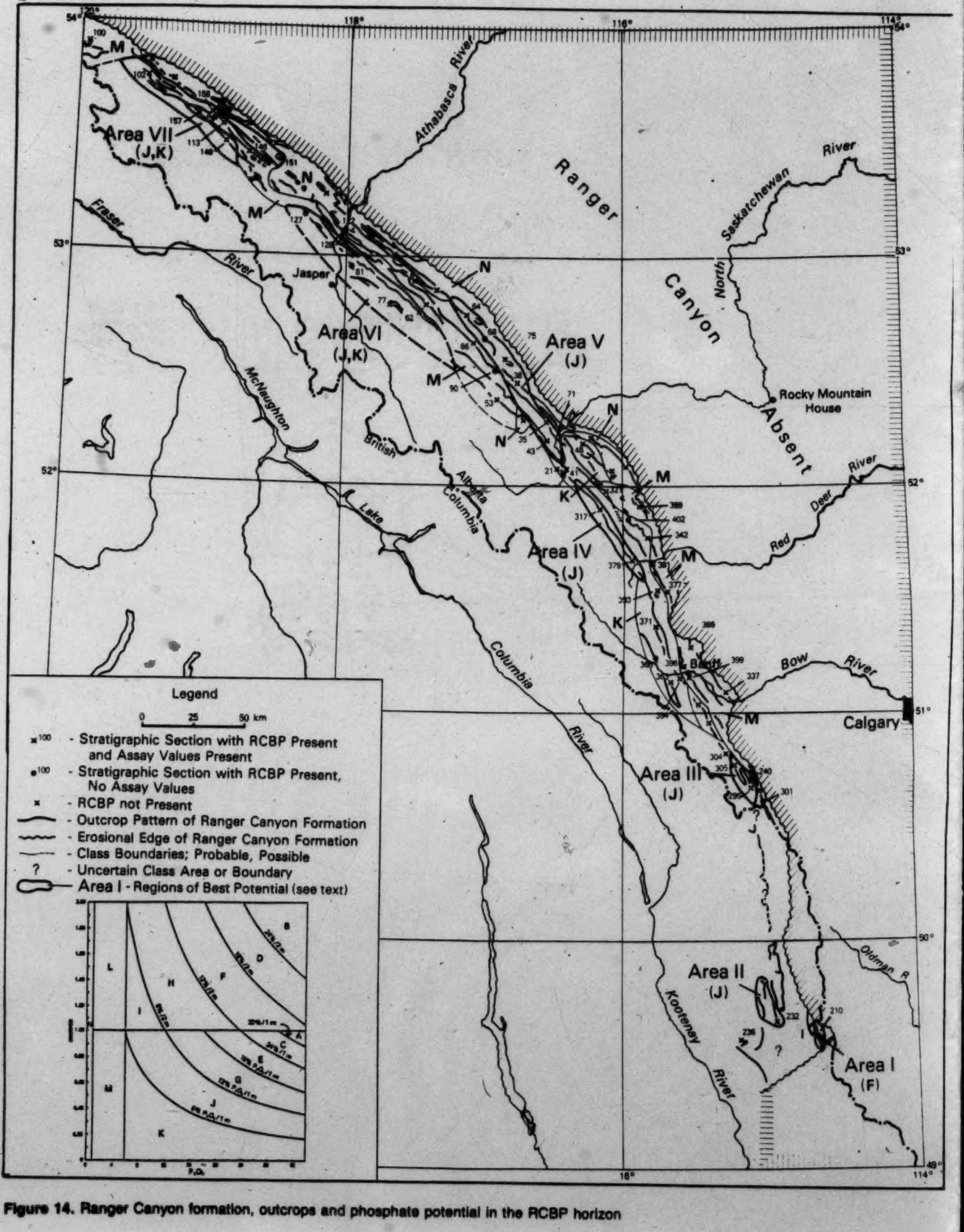
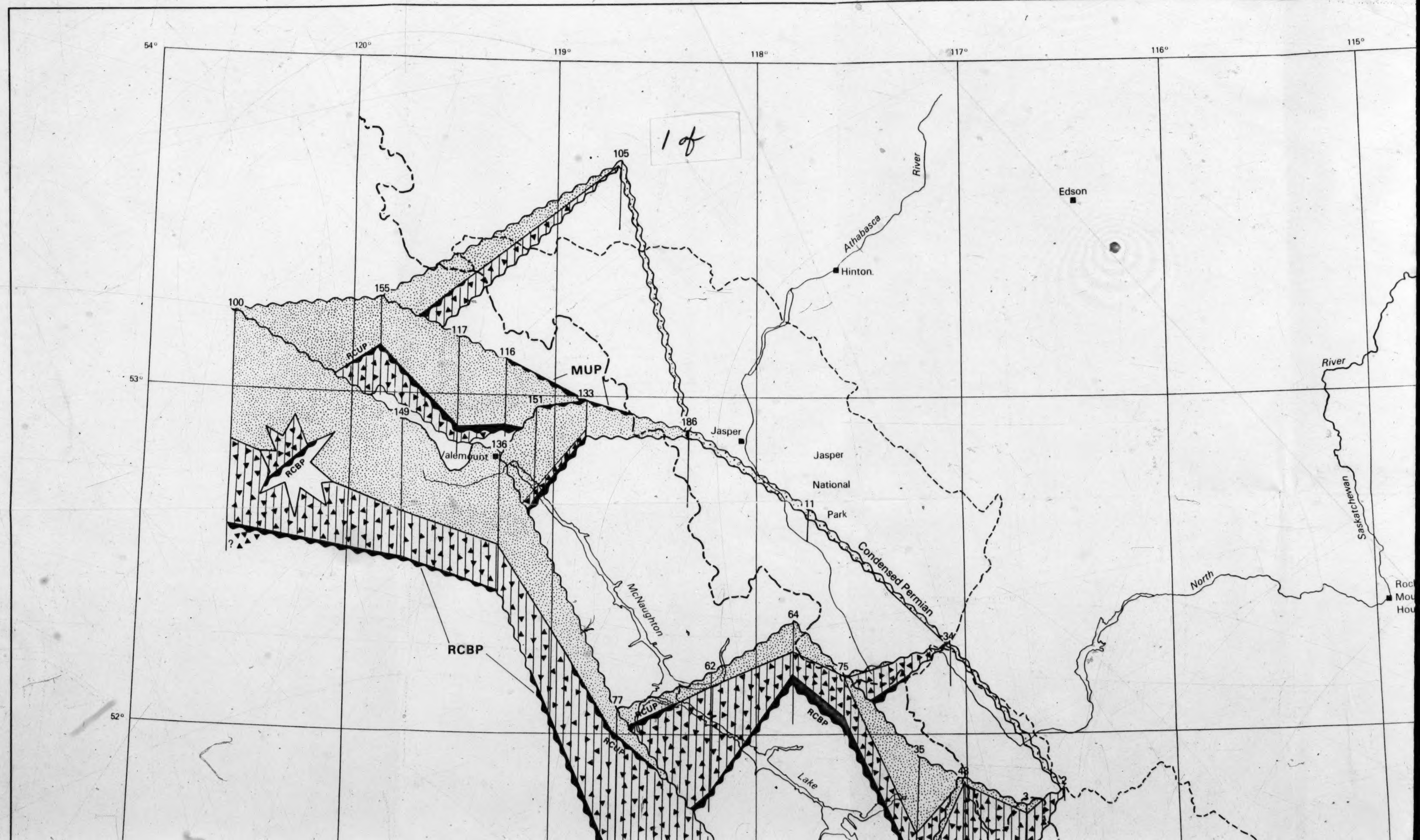
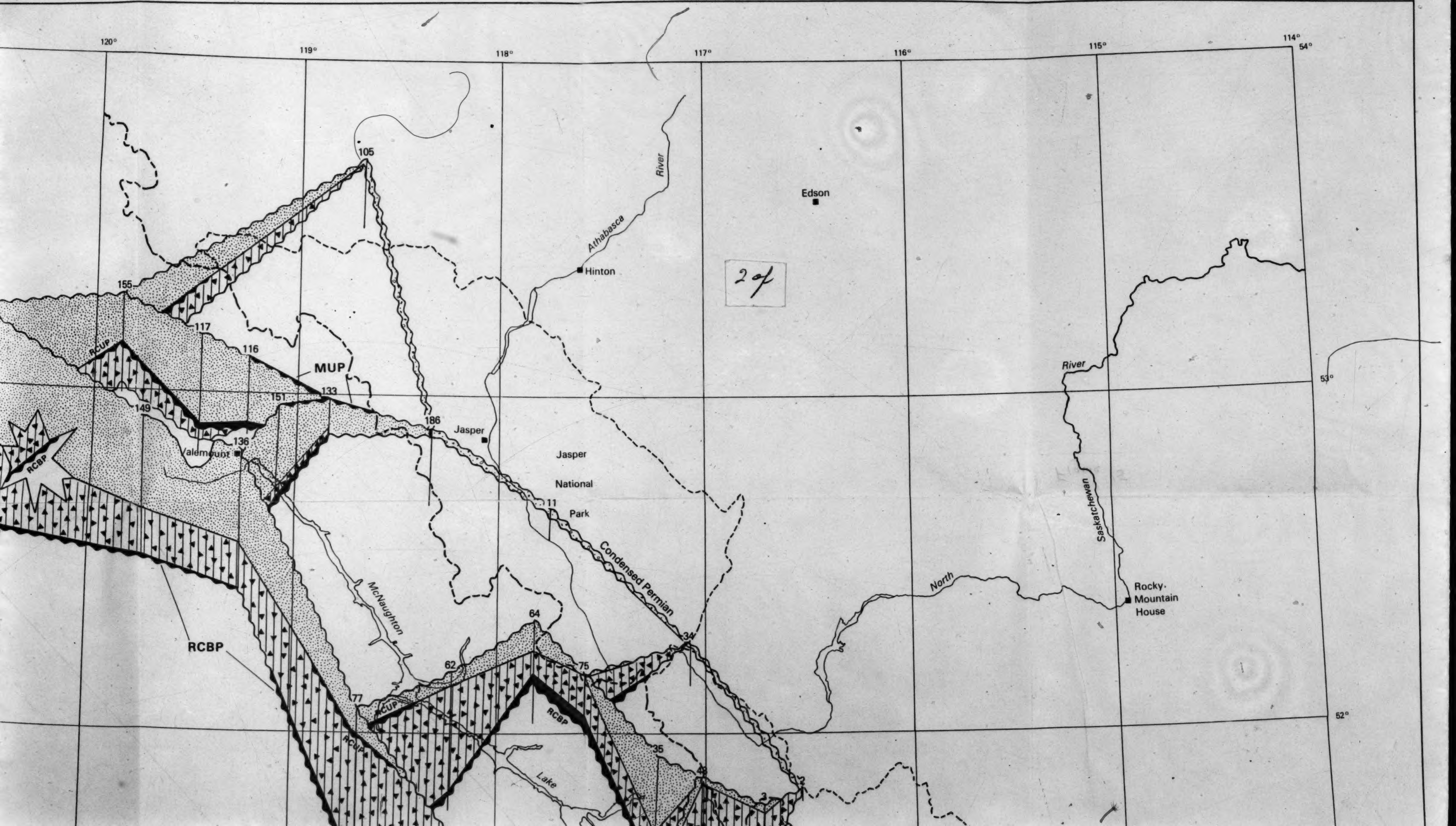


54°
120°
118°
116°
114°
53°
52°
51°
50°
49°
Area VII
(J,K)
Area VI
(J,K)
Area V
(J)
Area IV
(J)
Area III
(J)
Area II
(J)
Area I
(F)
M
N
K
J
Ranger
Canyon
Absent
Athabasca River
Fraser River
Jasper
McNaughton
British
Columbia
Alberta
Lake
Columbia River
North Saskatchewan River
Rocky Mountain House
Red Deer River
Bow River
Banff
Calgary
Kootenay River
Oldman R
Legend
0
25
50 km
100 - Stratigraphic Section with RCBP Present and Assay Values Present
100 - Stratigraphic Section with RCBP Present, No Assay Values
- RCBP not Present
- Outcrop Pattern of Ranger Canyon Formation
- Erosional Edge of Ranger Canyon Formation
- Class Boundaries; Probable, Possible
? - Uncertain Class Area or Boundary
Area I - Regions of Best Potential (see text)
A
B
C
D
E
F
G
H
I
J
K
L
M
P₂O₅

Figure 14. Ranger Canyon formation, outcrops and phosphate potential in the RCBP horizon

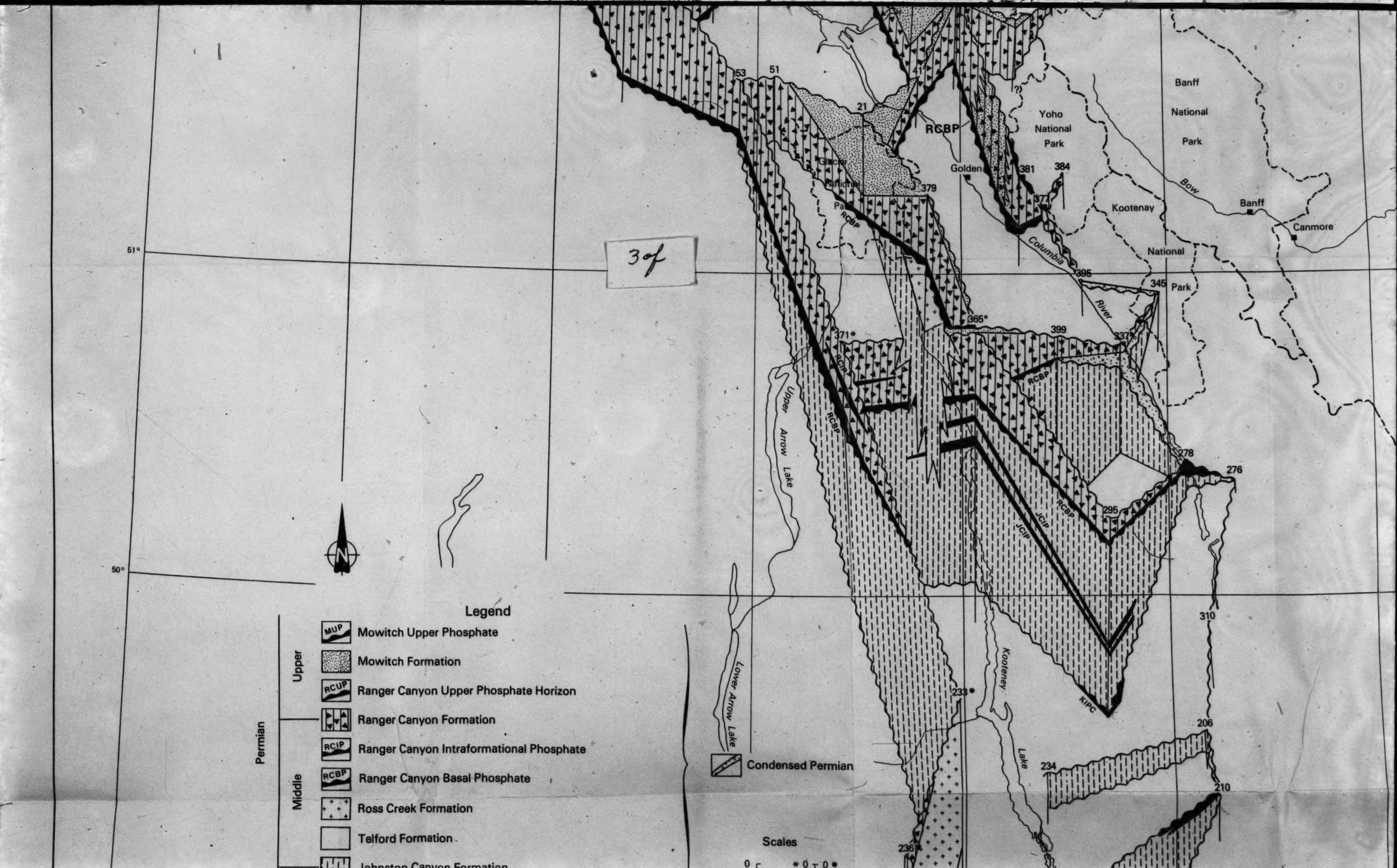

54°
120°
119°
118°
117°
116°
115°
53°
52°
105
Edson
Athabasca
River
Hinton
100
155
117
116
RCUP
MUP
133
151
149
136
Valemount
RCBP
186
Jasper
Jasper
National
Park
11
Condensed Permian
River
Saskatchewan
North
Roc
Mou
Hou
McNaughton
RCBP
64
62
75
34
77
RCUP
RCUP
RCBP
35
Lake
43
3
2
?

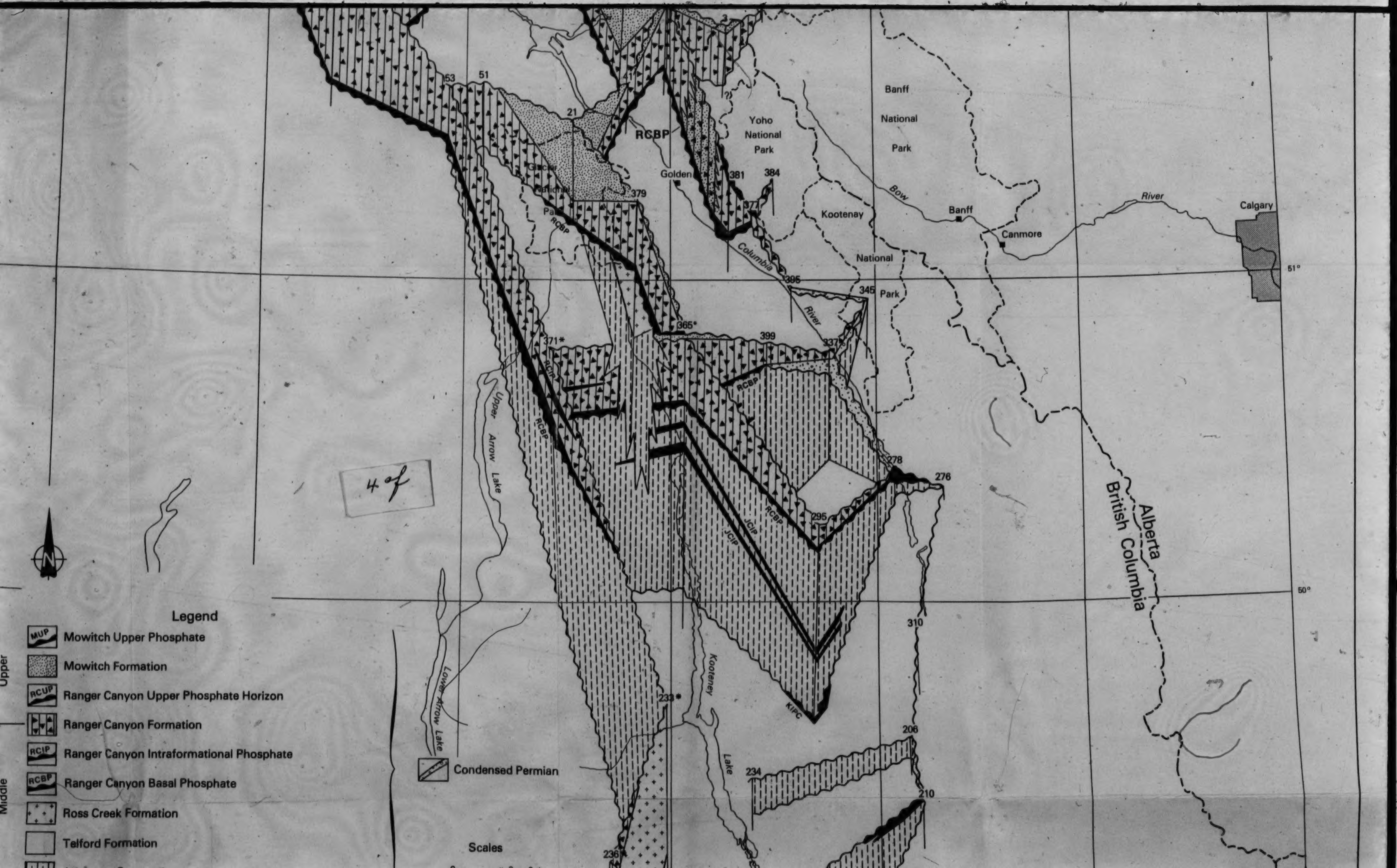
1 of


120°
119°
118°
117°
116°
115°
114°
54°
53°
52°
105
Athabasca
River
Edson
Hinton
155
117
116
MUP
RCUP
133
151
149
186
Jasper
136
Valemount
RCBP
Jasper
National
Park
11
Condensed Permian
McNaughton
River
Saskatchewan
North
Rocky
Mountain
House
64
62
75
34
RCBP
77
RCUP
RCBP
RCUP
35
48
3
Lake

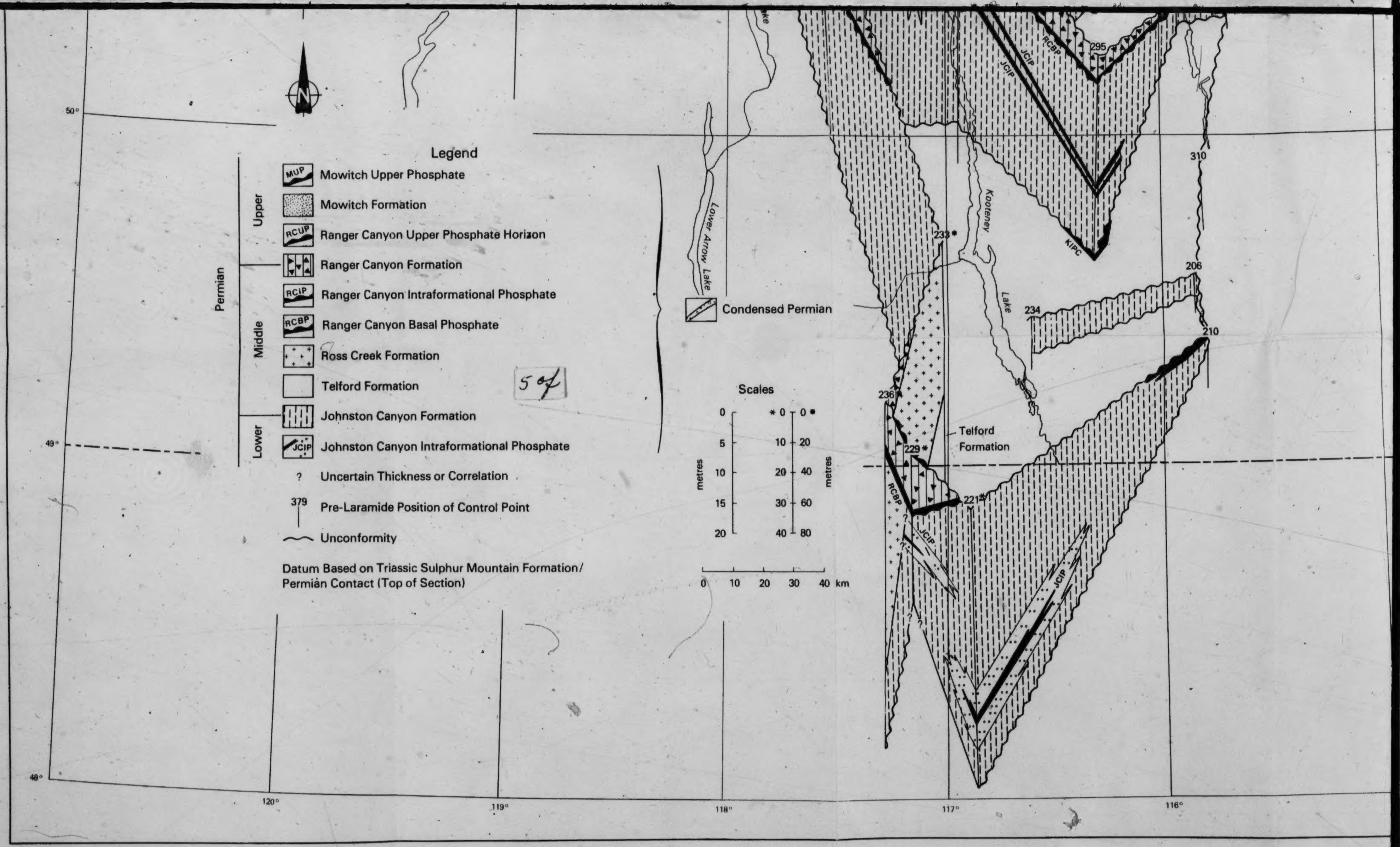
2 of

3 of


Legend
Permian
Upper
Middle
MUP Mowitch Upper Phosphate
Mowitch Formation
RCUP Ranger Canyon Upper Phosphate Horizon
Ranger Canyon Formation
RCIP Ranger Canyon Intraformational Phosphate
RCBP Ranger Canyon Basal Phosphate
Ross Creek Formation
Telford Formation
Johnston Canyon Formation
Condensed Permian
Scales
51°
50°
N
Banff National Park
Yoho National Park
Kootenay National Park
Glacier National Park
Golden
Banff
Canmore
Bow
Columbia River
Upper Arrow Lake
Lower Arrow Lake
Kootenay Lake
RCBP
RCIP
JCIP
KIPC
53
51
21
379
381
384
377
395
345
365*
371*
399
337*
278
276
295
310
233*
234
206
210
236*
3
41
?

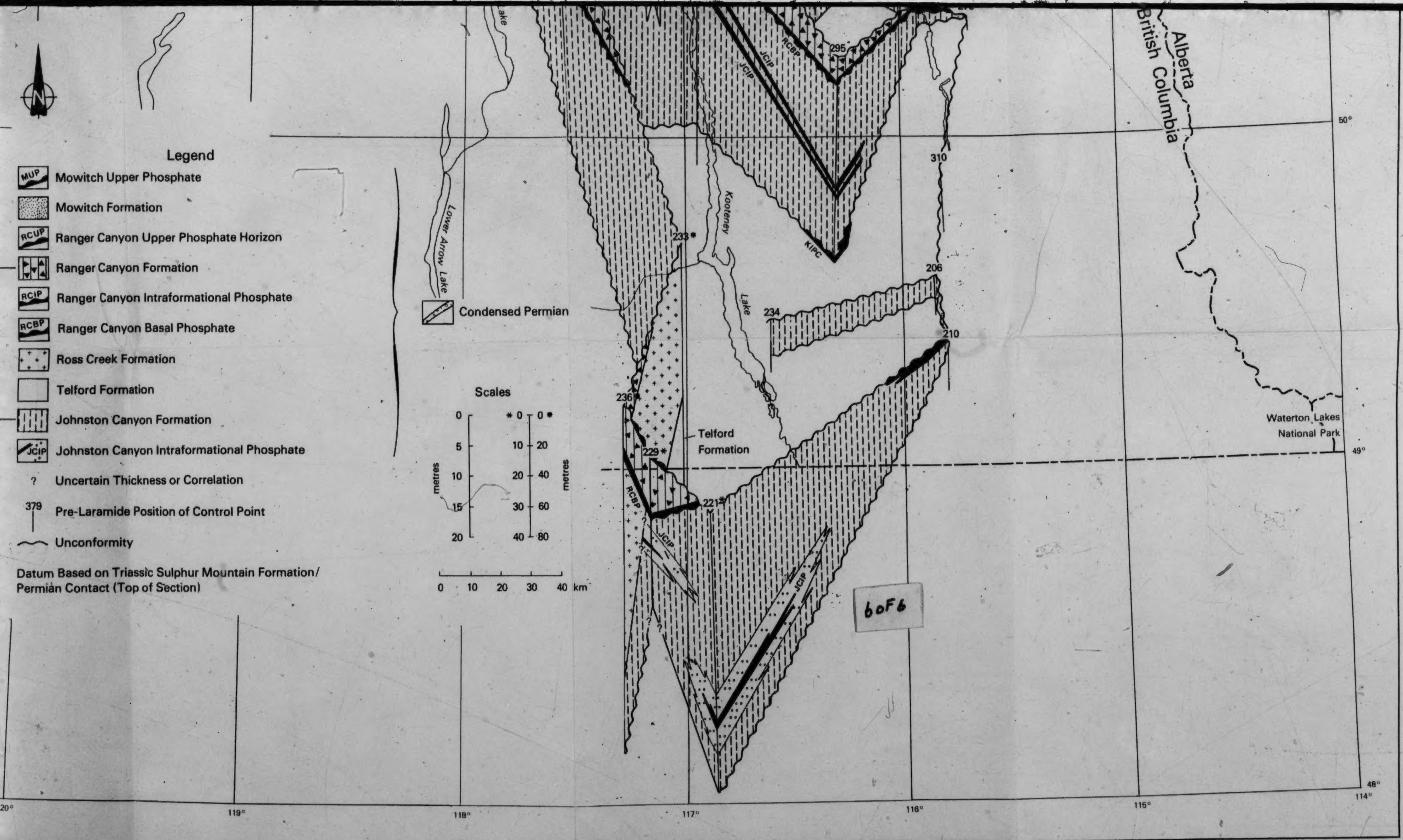

Banff
National
Park
Yoho
National
Park
Golden
RCBP
Glacier
National
Park
Kootenay
National
Park
Bow
River
Banff
Canmore
Calgary
51°
50°
Columbia
River
Alberta
British Columbia
Upper
Arrow
Lake
Lower Arrow Lake
Kootenay
Lake
3
53
51
21
379
381
384
305
345
365*
371*
399
337*
278
276
295
310
206
210
234
233*
236
RCIP
RCBP
JCIP
KIPC
Condensed Permian
Scales
Legend
Upper
Middle
MUP Mowitch Upper Phosphate
Mowitch Formation
RCUP Ranger Canyon Upper Phosphate Horizon
Ranger Canyon Formation
RCIP Ranger Canyon Intraformational Phosphate
RCBP Ranger Canyon Basal Phosphate
Ross Creek Formation
Telford Formation

4 of


Legend
Permian
Upper
Middle
Lower
MUP Mowitch Upper Phosphate
Mowitch Formation
RCUP Ranger Canyon Upper Phosphate Horizon
Ranger Canyon Formation
RCIP Ranger Canyon Intraformational Phosphate
RCBP Ranger Canyon Basal Phosphate
Ross Creek Formation
Telford Formation
Johnston Canyon Formation
JCIP Johnston Canyon Intraformational Phosphate
? Uncertain Thickness or Correlation
379 Pre-Laramide Position of Control Point
Unconformity
Datum Based on Triassic Sulphur Mountain Formation/ Permian Contact (Top of Section)
Condensed Permian
Scales
metres
0 5 10 15 20
* 0 10 20 30 40
0 * 20 40 60 80
0 10 20 30 40 km
Lower Arrow Lake
Kootenay Lake
Telford Formation
RCBP
JCIP
KIPC
295
310
233*
206
234
210
236
229*
221*
50°
49°
48°
120°
119°
118°
117°
116°

5 of

Figure 15. Fence diagram illustrating Permian stratigraphy and phosphate horizons — Palinspastically restored and Permo-Pennsylvanian stratigraphic section location map


Legend
MUP Mowitch Upper Phosphate
Mowitch Formation
RCUP Ranger Canyon Upper Phosphate Horizon
Ranger Canyon Formation
RCIP Ranger Canyon Intraformational Phosphate
RCBP Ranger Canyon Basal Phosphate
Ross Creek Formation
Telford Formation
Johnston Canyon Formation
JCIP Johnston Canyon Intraformational Phosphate
? Uncertain Thickness or Correlation
379 Pre-Laramide Position of Control Point
Unconformity
Datum Based on Triassic Sulphur Mountain Formation/Permian Contact (Top of Section)
Condensed Permian
Scales
metres
0
5
10
15
20
0
10
20
30
40
0
20
40
60
80
0 10 20 30 40 km
Lower Arrow Lake
Lake
Kooteney Lake
Telford Formation
Alberta
British Columbia
Waterton Lakes National Park
RCBP
JCIP
KIPC
295
310
233
206
234
210
236
229
221
50°
49°
48°
120°
119°
118°
117°
116°
115°
114°

6oF6

and phosphate horizons — Palinspastically
ation map

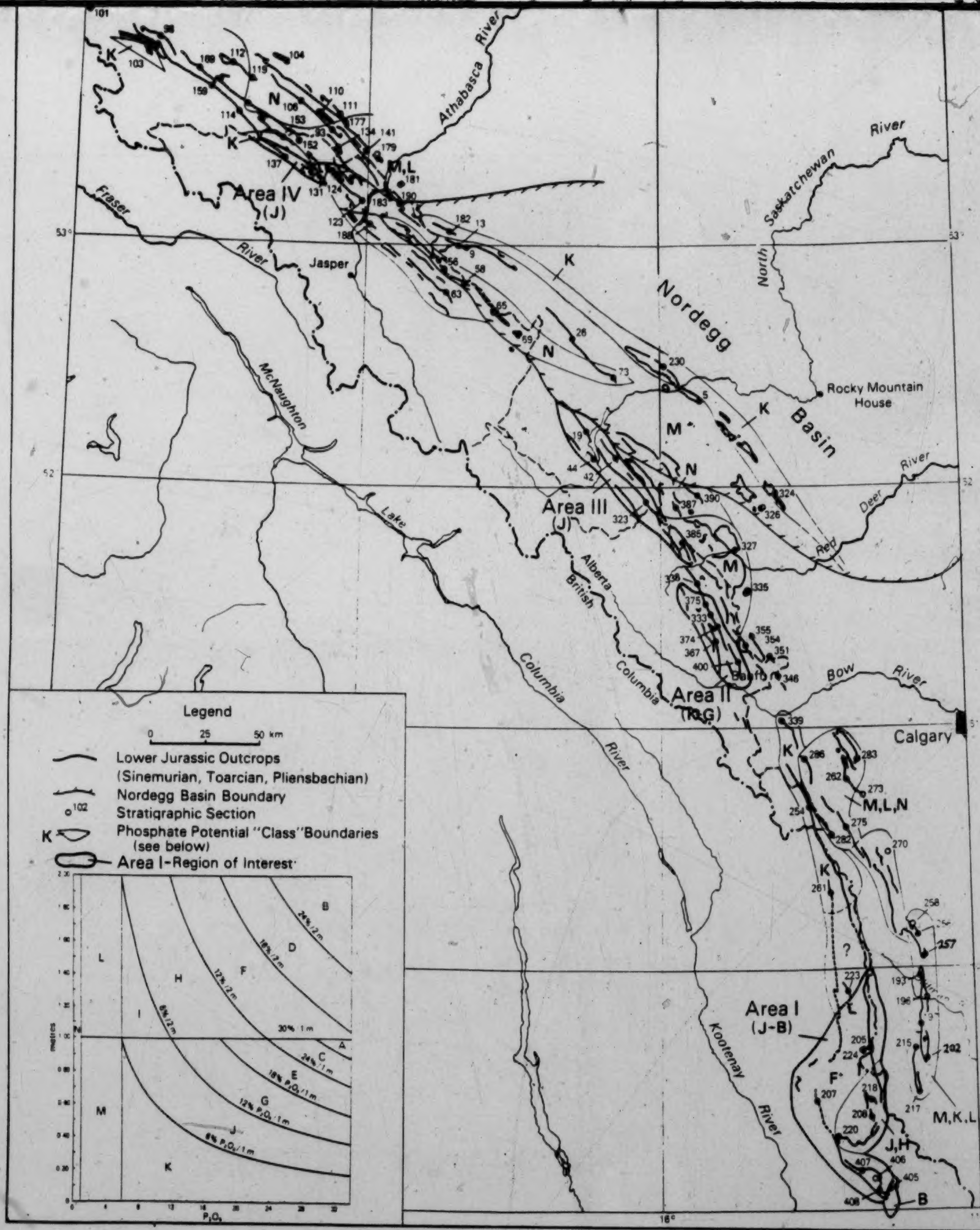
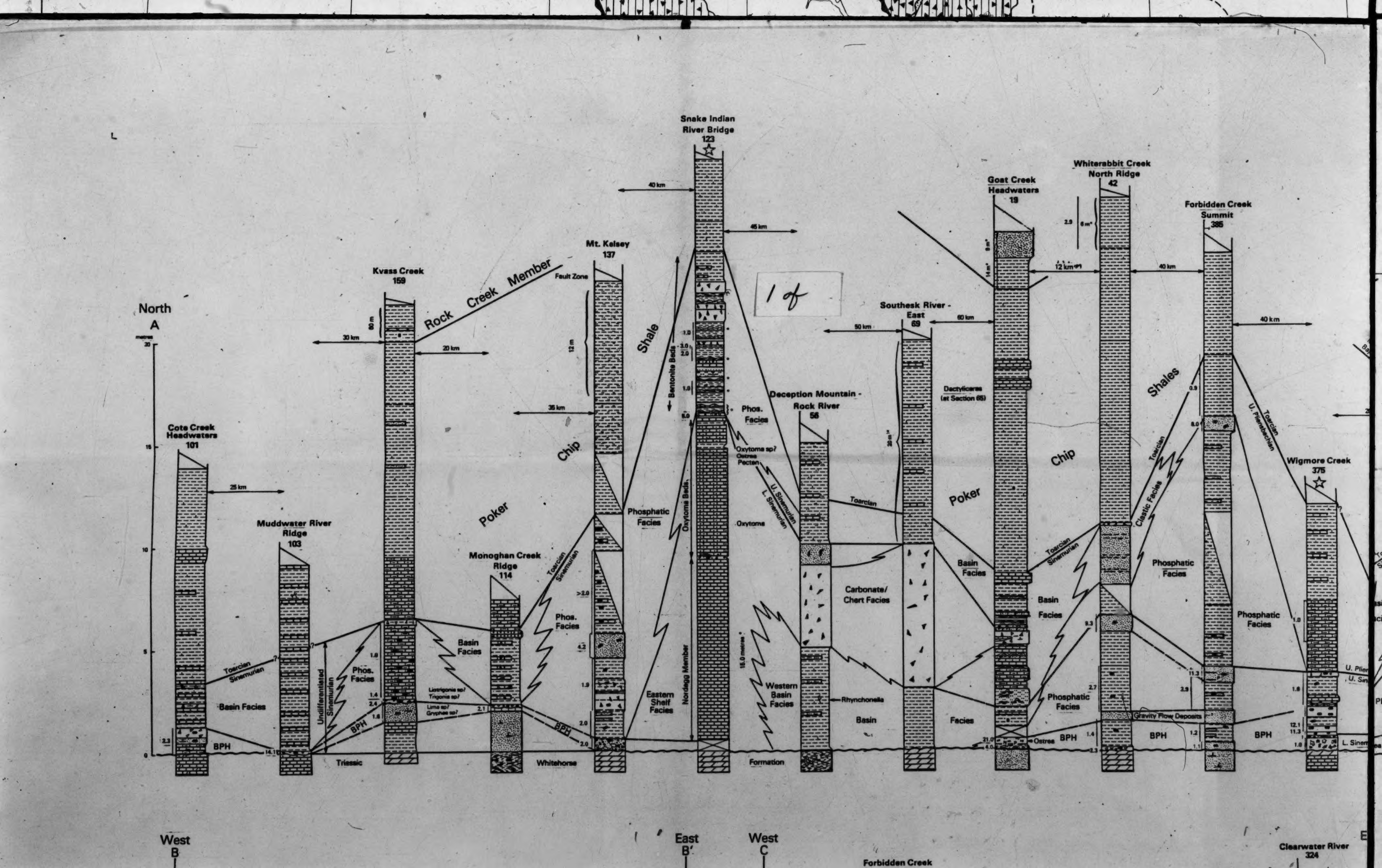
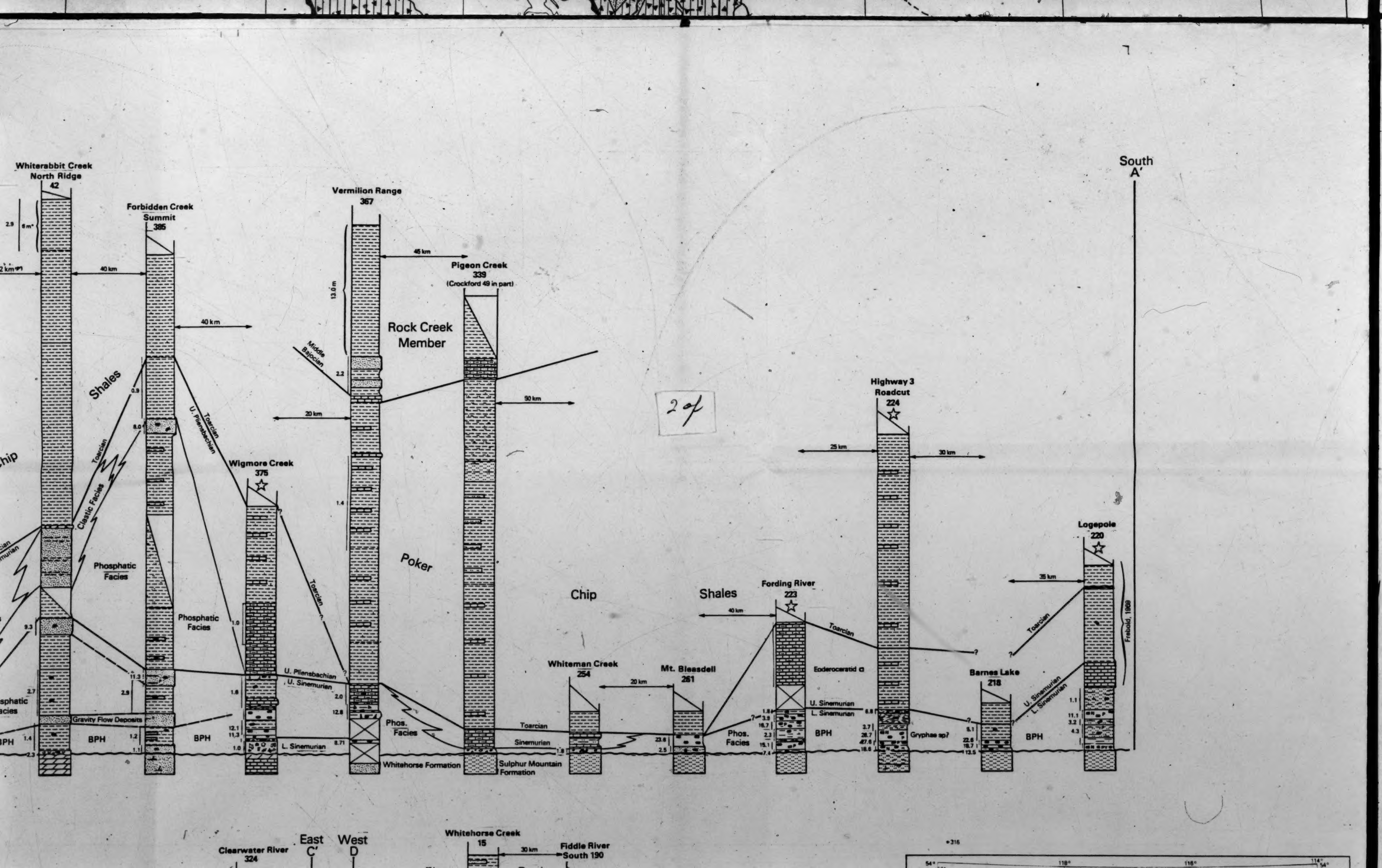

Athabasca River
Fraser River
Jasper
McNaughton Lake
Columbia River
Kootenay River
North Saskatchewan River
Rocky Mountain House
Red Deer River
Bow River
Calgary
Banff
Nordegg Basin
Alberta
British Columbia
Area IV (J)
Area III (J)
Area II (K,G)
Area I (J-B)
M,L
M,L,N
M,K,L
J,H
K
N
M
L
F
B
?
53°
52°
51°
50°
49
114°
116°
Legend
0 25 50 km
Lower Jurassic Outcrops
(Sinemurian, Toarcian, Pliensbachian)
Nordegg Basin Boundary
102
Stratigraphic Section
K
Phosphate Potential "Class" Boundaries
(see below)
Area I-Region of Interest
metres
P_2O_5
24%/2m
18%/2m
12%/2m
6%/2m
30% 1m
24%/1m
18% P_2O_5/1m
12% P_2O_5/1m
6% P_2O_5/1m
A
B
C
D
E
F
G
H
I
J
K
L
M
N

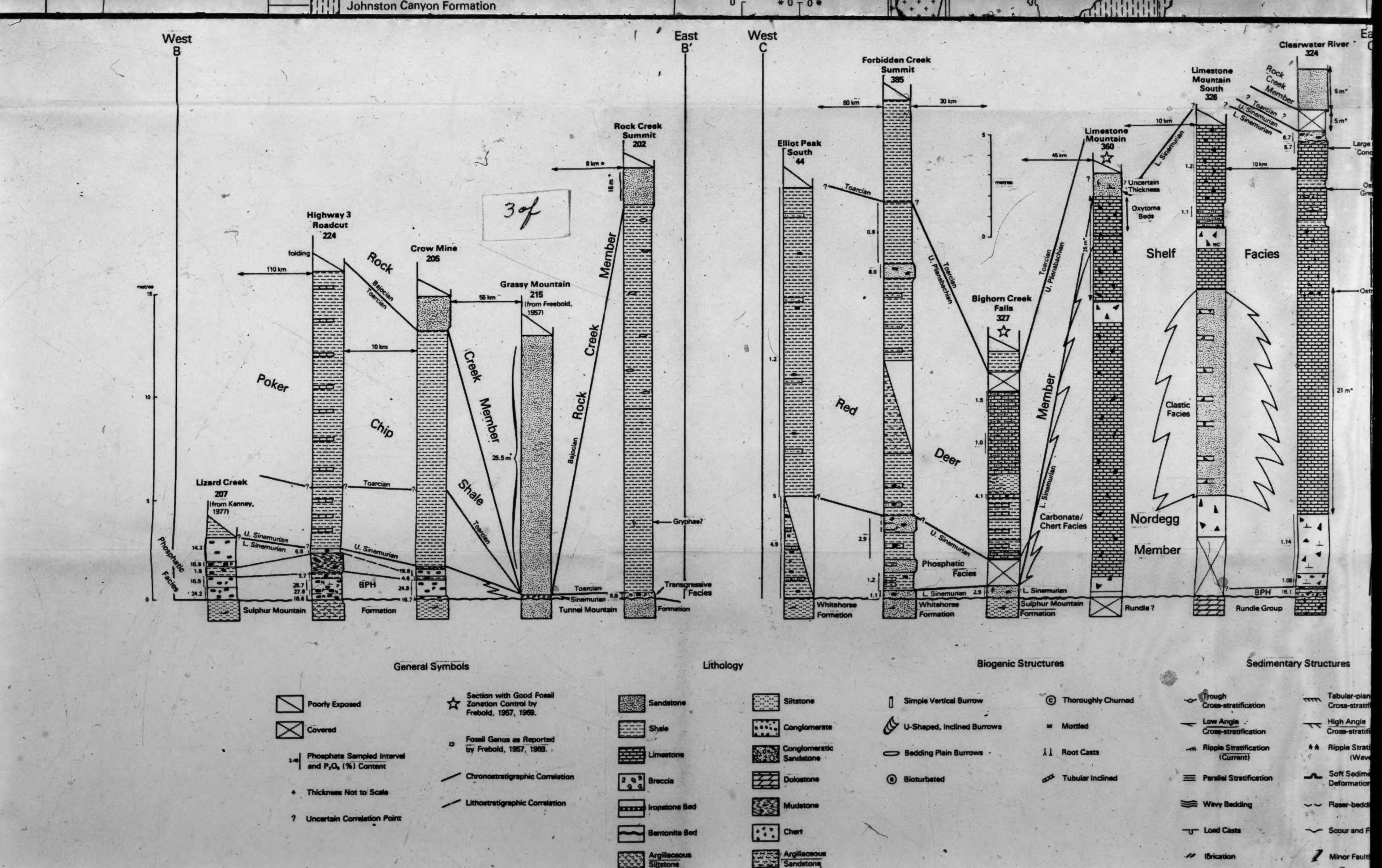
Figure 20. Lower Jurassic outcrops and phosphate potential — Fernie Group


North
A
metres
20
15
10
5
0
Cote Creek Headwaters
101
25 km
Basin Facies
BPH
Toarcian
Sinemurian
Muddwater River Ridge
103
Undifferentiated Sinemurian
Triassic
Kvass Creek
159
30 km
20 km
80 m
Rock Creek Member
Phos. Facies
BPH
Poker
Basin Facies
Liotrigonia sp?
Trigonia sp?
Lima sp?
Gryphea sp?
Monoghan Creek Ridge
114
Whitehorse
Toarcian
Sinemurian
Phos. Facies
Mt. Kelsey
137
Fault Zone
12 m
35 km
Chip
BPH
Shale
Phosphatic Facies
Eastern Shelf Facies
40 km
Snake Indian River Bridge
123
45 km
Bentonite Beds
Oxytoma Beds
Nordegg Member
Phos. Facies
Oxytoma sp?
Ostrea
Pecten
U. Sinemurian
L. Sinemurian
Oxytoma
Formation
16.0 metres
Western Basin Facies
Deception Mountain - Rock River
56
Rhynchonella
Basin
Carbonate/ Chert Facies
Toarcian
Southesk River - East
69
50 km
60 km
30 m
Dactylicaras (at Section 65)
Poker
Facies
Basin Facies
Goat Creek Headwaters
19
9 m
14 m
Basin Facies
Ostrea
BPH
Chip
Toarcian
Sinemurian
Phosphatic Facies
12 km
Whiterabbit Creek North Ridge
42
6 m
Shales
Toarcian
Clastic Facies
Phosphatic Facies
Gravity Flow Deposits
BPH
40 km
Forbidden Creek Summit
385
40 km
U. Pliensbachian
Toarcian
Phosphatic Facies
BPH
Wigmore Creek
375
U. Plien
U. Sin
L. Sinem
West
B
East
B′
West
C
Forbidden Creek
Clearwater River
324
E

1 of


Whiterabbit Creek North Ridge 42
Forbidden Creek Summit 385
Vermilion Range 367
Pigeon Creek 339 (Crockford 49 in part)
Wigmore Creek 375
Whiteman Creek 254
Mt. Bleasdell 261
Fording River 223
Highway 3 Roadcut 224
Barnes Lake 218
Logepole 220
South
A'
2 km
40 km
40 km
45 km
20 km
50 km
20 km
40 km
25 km
30 km
35 km
2.9
6 m*
13.0 m
Rock Creek Member
Middle Bajocian
Shales
Chip
Toarcian
U. Pliensbachian
Clastic Facies
Phosphatic Facies
Phosphatic Facies
Poker
Chip
Shales
Toarcian
Toarcian
Toarcian
U. Pliensbachian
U. Sinemurian
L. Sinemurian
Gravity Flow Deposits
BPH
BPH
BPH
BPH
Phos. Facies
Phos. Facies
Toarcian
Sinemurian
Whitehorse Formation
Sulphur Mountain Formation
Eoderoceratid
U. Sinemurian
L. Sinemurian
Gryphae sp?
U. Sinemurian
L. Sinemurian
Frebold, 1969
0.9
8.0
2.2
1.4
9.3
2.7
2.9
11.3
1.4
2.3
1.2
1.1
1.0
1.6
12.1
11.3
1.0
2.0
12.8
8.71
1.8
23.6
2.5
1.8
3.9
16.7
2.3
15.1
7.4
6.8
3.7
28.7
47.6
18.6
5.1
22.6
18.7
13.5
1.1
11.1
3.2
4.3
Clearwater River 324
East C'
West D
Whitehorse Creek 15
30 km
Fiddle River South 190
316
54°
118°
116°
114°
54°

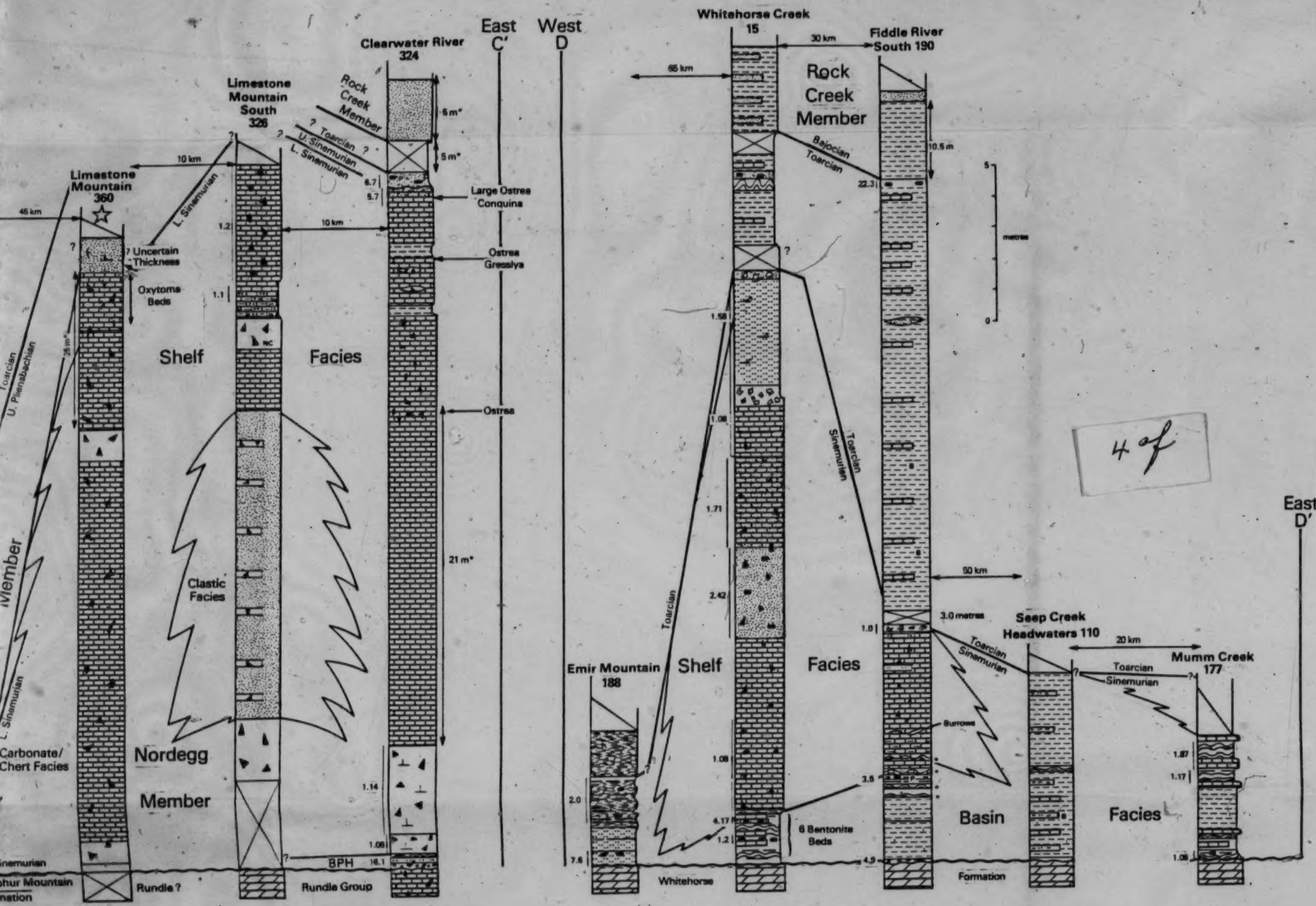
2 of


Johnston Canyon Formation
West
B
East
B′
West
C
Ea
C
Lizard Creek
207
(from Kenney, 1977)
Highway 3 Roadcut
224
folding
110 km
Crow Mine
205
10 km
Grassy Mountain
215
(from Frebold, 1957)
55 km
Rock Creek Summit
202
8 km *
16 m*
25.5 m*
Elliot Peak South
44
Forbidden Creek Summit
385
60 km
30 km
Bighorn Creek Falls
327
Limestone Mountain
360
45 km
Limestone Mountain South
326
10 km
Clearwater River
324
10 km
5 m*
5 m*
21 m*
metres
15
10
5
0
Poker
Chip
Shale
Rock
Creek
Member
Bajocian
Toarcian
U. Sinemurian
L. Sinemurian
Phosphatic Facies
BPH
Sulphur Mountain
Formation
Tunnel Mountain
Formation
Sinemurian
Transgressive Facies
Gryphea?
14.3
10.9
1.6
10.9
24.2
6.8
3.7
28.7
27.8
18.6
19.6
4.6
24.9
18.7
6.8
Red
Deer
Member
U. Pliensbachian
Phosphatic Facies
L. Sinemurian
Whitehorse Formation
Sulphur Mountain Formation
Carbonate/ Chert Facies
Uncertain Thickness
Oxytoma Beds
26 m*
Shelf
Facies
Clastic Facies
Nordegg
Member
Rundle ?
Rundle Group
Rock Creek Member
Toarcian
U. Sinemurian
L. Sinemurian
Large Conc
Ost Gre
Ostr
1.2
4.9
5
0.9
8.0
2.9
1.2
1.1
1.5
1.0
4.1
2.9
1.2
1.1
1.14
1.08
16.1
6.7
5.7
?
General Symbols
Poorly Exposed
Covered
Phosphate Sampled Interval and P₂O₅ (%) Content
Thickness Not to Scale
Uncertain Correlation Point
Section with Good Fossil Zonation Control by Frebold, 1957, 1969.
Fossil Genus as Reported by Frebold, 1957, 1969.
Chronostratigraphic Correlation
Lithostratigraphic Correlation
Lithology
Sandstone
Shale
Limestone
Breccia
Ironstone Bed
Bentonite Bed
Argillaceous Siltstone
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Chert
Argillaceous Sandstone
Biogenic Structures
Simple Vertical Burrow
U-Shaped, Inclined Burrows
Bedding Plain Burrows
Bioturbated
Thoroughly Churned
Mottled
Root Casts
Tubular Inclined
Sedimentary Structures
Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Load Casts
Ibrication
Tabular-plan Cross-stratif
High Angle Cross-stratif
Ripple Strati (Wav
Soft Sedim Deformation
Flaser-beddi
Scour and F
Minor Fault

3 of

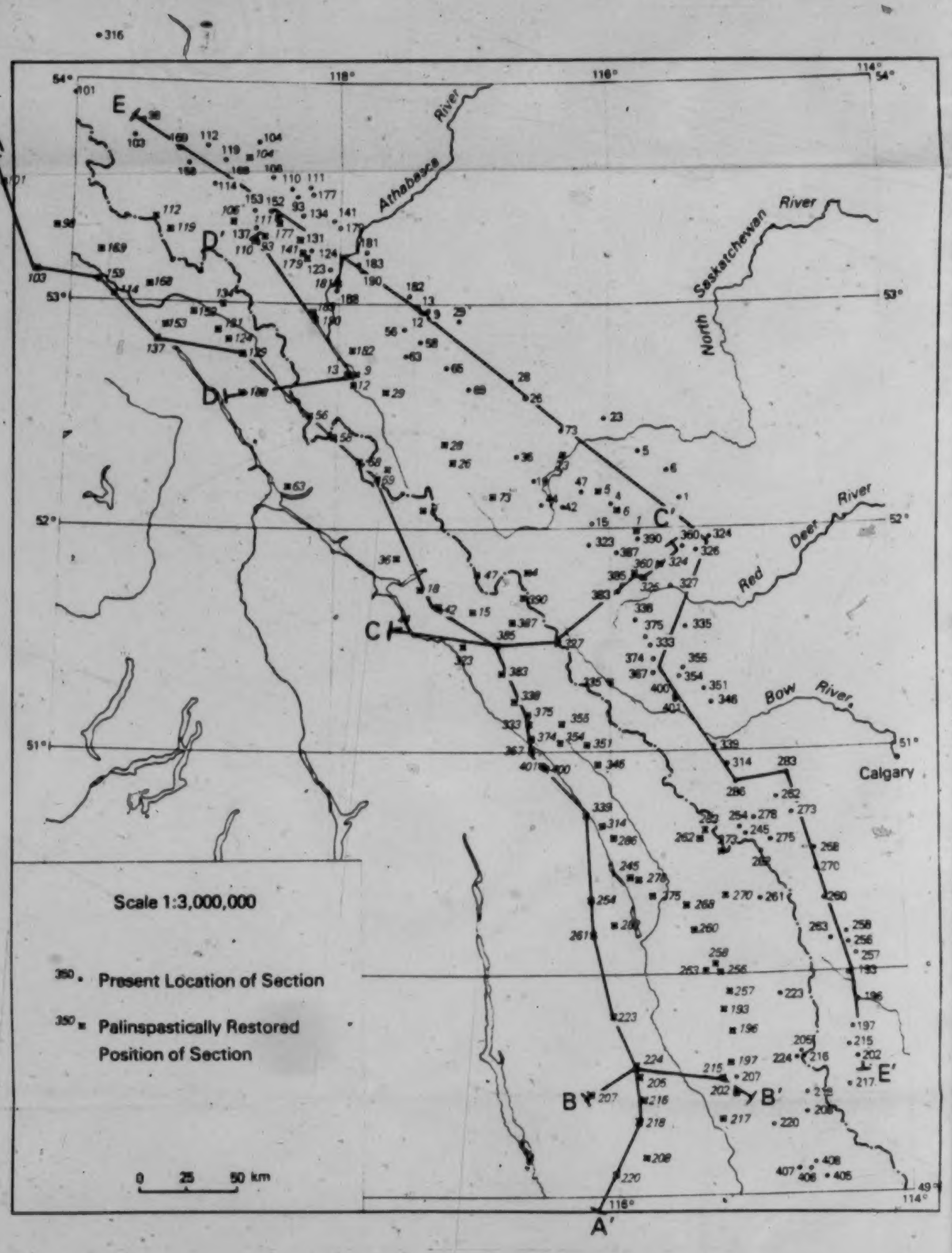
Johnston Canyon Formation

Waterton Lakes



Limestone Mountain 360
Limestone Mountain South 326
Clearwater River 324
East C'
West D
Whitehorse Creek 15
Fiddle River South 190
Emir Mountain 188
Seep Creek Headwaters 110
Mumm Creek 177
East D'
45 km
10 km
10 km
30 km
65 km
50 km
20 km
Rock Creek Member
? Toarcian ?
U. Sinemurian
L. Sinemurian
Bajocian
Toarcian
Toarcian
Sinemurian
Toarcian
U. Pliensbachian
L. Sinemurian
? Uncertain Thickness
Oxytoma Beds
Large Ostrea Conquina
Ostrea Gresslya
Ostrea
Shelf
Facies
Clastic Facies
Carbonate/ Chert Facies
Nordegg
Member
Shelf
Facies
Basin
Facies
Burrows
6 Bentonite Beds
3.0 metres
10.5 m
6 m*
5 m*
21 m*
26 m*
metres
5
0
BPH
Rundle ?
Rundle Group
Whitehorse
Formation
Sinemurian
Sulphur Mountain
Formation

4 of



A
A'
B
B'
C
C'
D
D'
E
E'
54°
53°
52°
51°
118°
116°
114°
Athabasca River
North Saskatchewan River
Red Deer River
Bow River
Calgary
Scale 1:3,000,000
0 25 50 km

350 • Present Location of Section

350 ■ Palinspastically Restored Position of Section

uctures

© Thoroughly Churned

M Mottled

Root Casts

Tubular Inclined

Sedimentary Structures

Trough Cross-stratification

Low Angle Cross-stratification

Ripple Stratification (Current)

≡ Parallel Stratification

Wavy Bedding

Load Casts

Tabular-planar Cross-stratification

High Angle Cross-stratification

Ripple Stratification (Wave)

Soft Sediment Deformation

Flaser-bedding

Scour and Fill

Organic Remains

Carbonaceous Matter

Bones

Coal Chips

FF Fish Debris

P Phosphate Pellets or Oolites

Phosphate Pebbles

Transported Wood

Invertebrate Fossils

Belemnites

N Phosphate Nodules

Phosphatic (> 1% P_2O_5)

Cement and Accessory Minerals

G Glauconite

Bentonite

Fe Iron Oxide Cement

OO Ironstone Concretions

PY Pyrite

⊥ Calcareous

Sd Sideritic Cement

Dolomitic

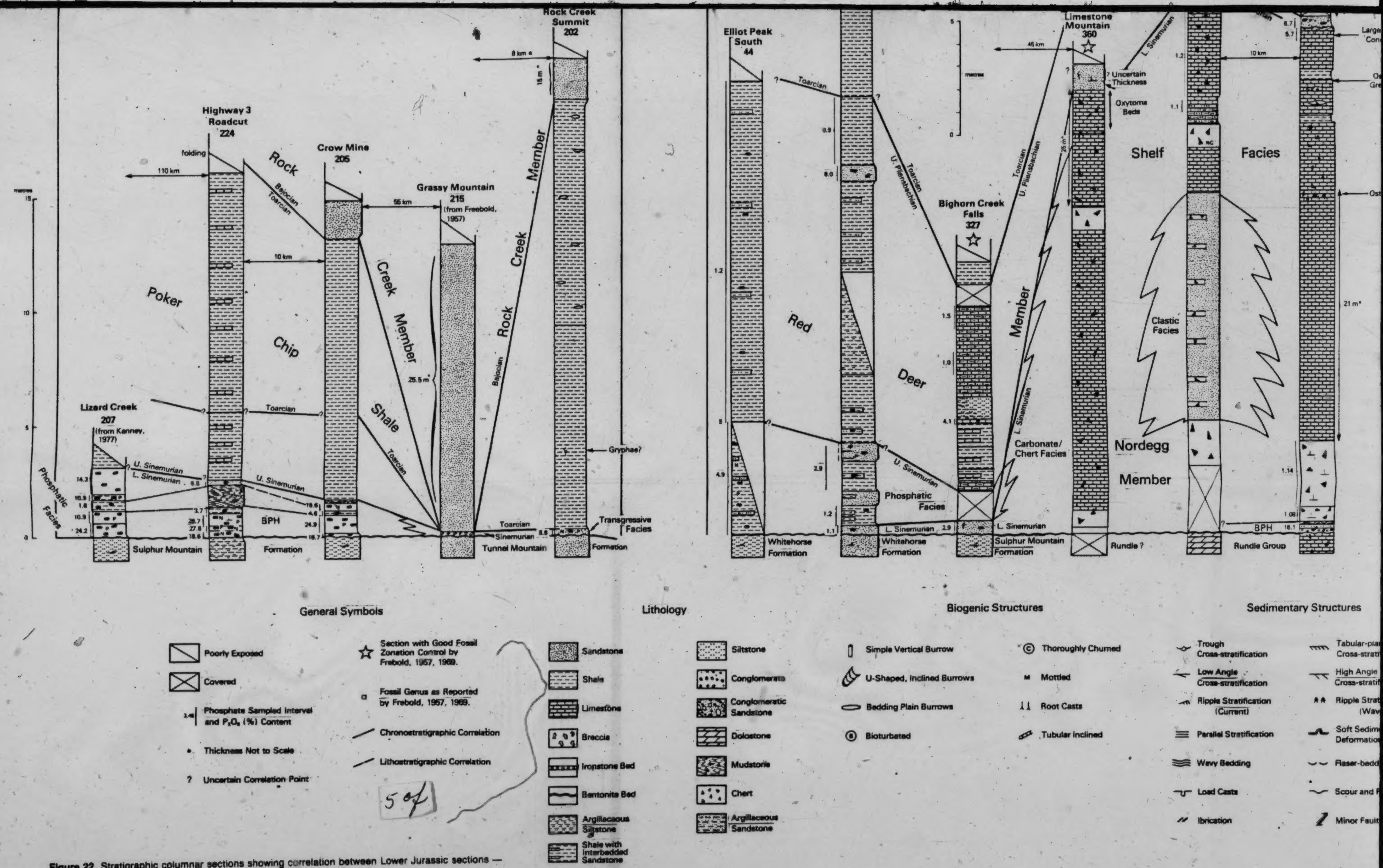
C Phosphate Cement

Sharp

Erosional and Unconformable

Gradational

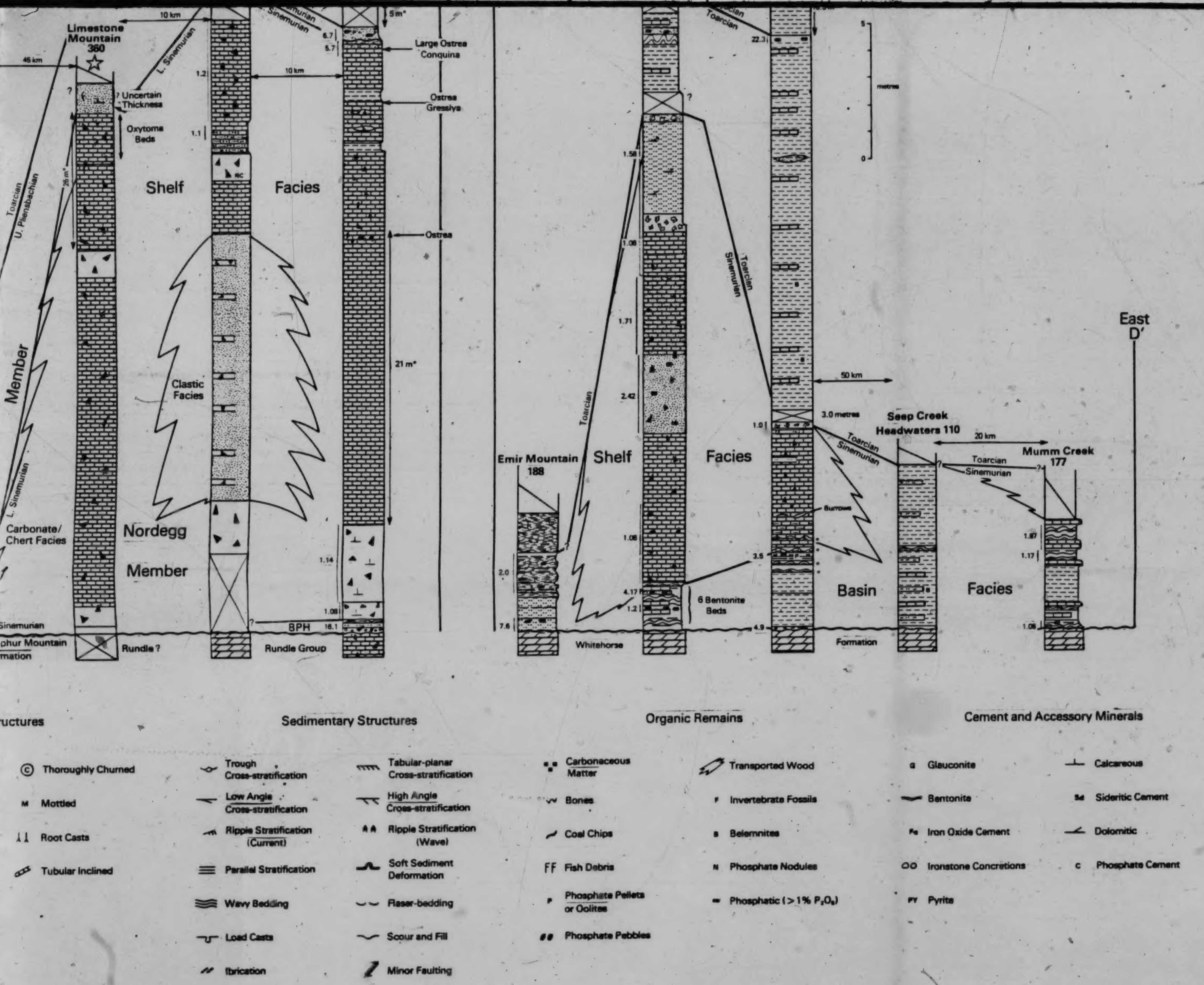
Obscured Contact

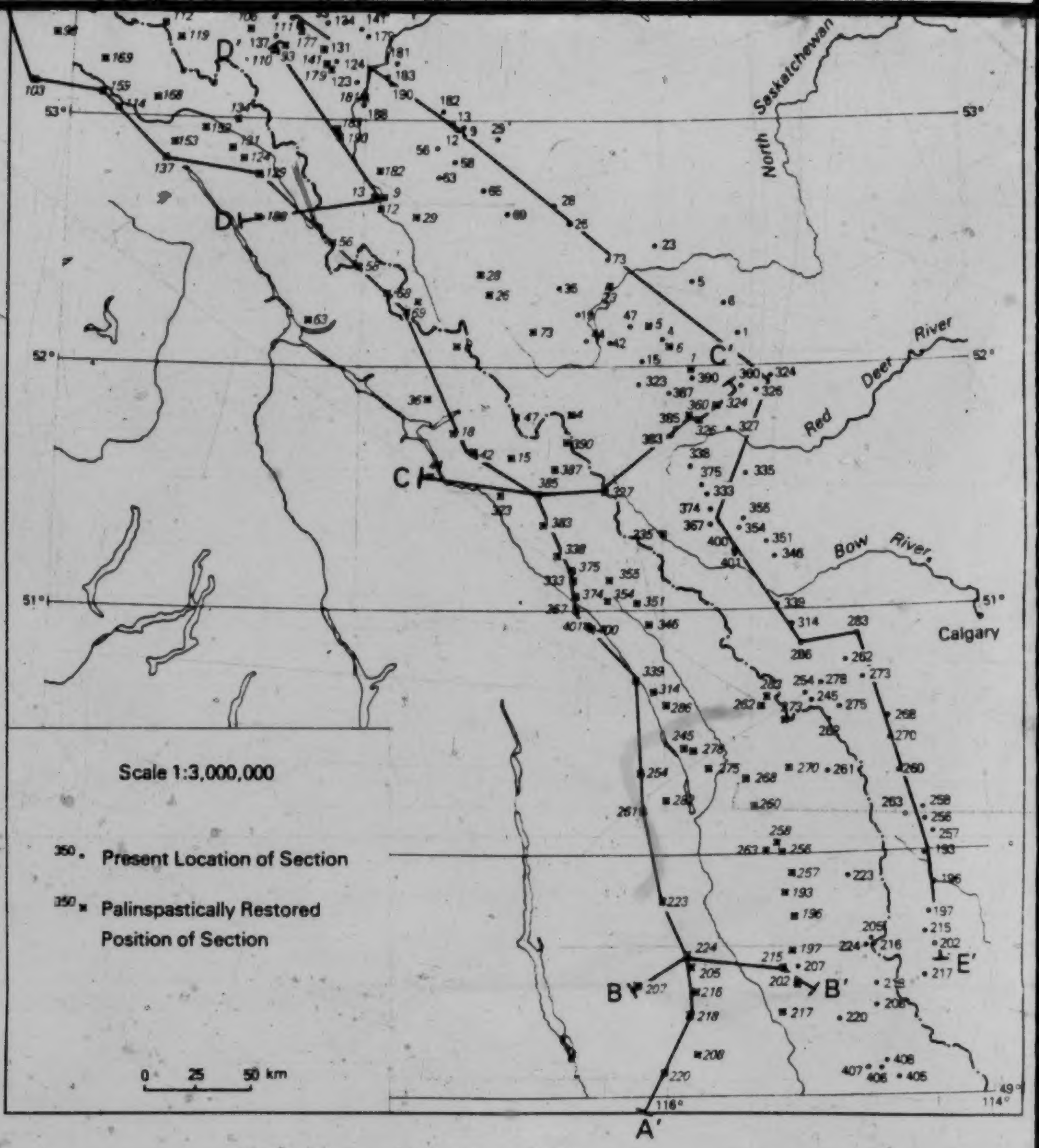


Lizard Creek 207 (from Kenney, 1977)
Highway 3 Roadcut 224
Crow Mine 205
Grassy Mountain 215 (from Freebold, 1957)
Rock Creek Summit 202
Elliot Peak South 44
Bighorn Creek Falls 327
Limestone Mountain 360
metres
15
10
5
0
110 km
10 km
56 km
8 km
45 km
10 km
folding
Poker Chip Shale
Rock Creek Member
Red Deer Member
Nordegg Member
Shelf Facies
Clastic Facies
Phosphatic Facies
Carbonate/ Chert Facies
Transgressive Facies
Bajocian
Toarcian
U. Sinemurian
L. Sinemurian
Sinemurian
U. Pliensbachian
Oxytoma Beds
? Uncertain Thickness
Gryphae?
BPH
25.5 m
15 m
25 m
21 m
Sulphur Mountain Formation
Tunnel Mountain Formation
Whitehorse Formation
Rundle ?
Rundle Group
General Symbols
Poorly Exposed
Covered
Phosphate Sampled Interval and P₂O₅ (%) Content
Thickness Not to Scale
? Uncertain Correlation Point
Section with Good Fossil Zonation Control by Frebold, 1957, 1969.
Fossil Genus as Reported by Frebold, 1957, 1969.
Chronostratigraphic Correlation
Lithostratigraphic Correlation
Lithology
Sandstone
Shale
Limestone
Breccia
Ironstone Bed
Bentonite Bed
Argillaceous Siltstone
Shale with Interbedded Sandstone
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Chert
Argillaceous Sandstone
Biogenic Structures
Simple Vertical Burrow
U-Shaped, Inclined Burrows
Bedding Plain Burrows
Bioturbated
Thoroughly Churned
Mottled
Root Casts
Tubular Inclined
Sedimentary Structures
Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Load Casts
Ibrication
Tabular-pla
High Angle Cross-strati
Ripple Strat (Wav
Soft Sedim Deformatio
Flaser-bedd
Scour and F
Minor Fault

5 of

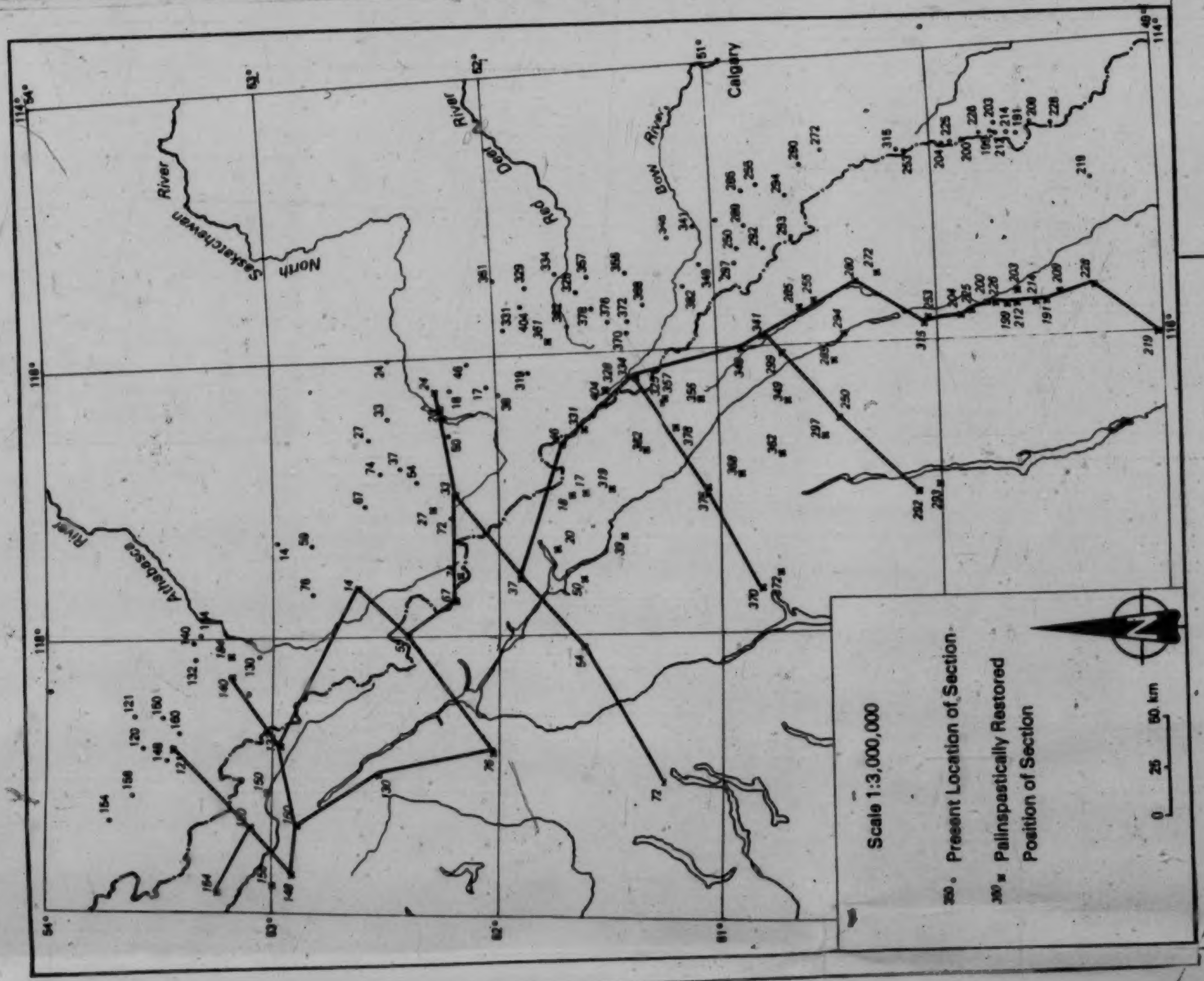
Figure 22. Stratigraphic columnar sections showing correlation between Lower Jurassic sections — Front ranges and foothills, Alberta and British Columbia


Limestone Mountain 360
10 km
45 km
? Uncertain Thickness
Oxytoma Beds
Shelf
Facies
Clastic Facies
Nordegg
Member
Carbonate/ Chert Facies
Toarcian
U. Pliensbachian
L. Sinemurian
Sinemurian
Member
Large Ostrea Conquina
Ostrea Gresslya
Ostrea
21 m*
5 m*
BPH
Rundle ?
Rundle Group
phur Mountain
mation
Emir Mountain 188
Shelf
Facies
Toarcian
Sinemurian
6 Bentonite Beds
Whitehorse
metres
50 km
3.0 metres
Seep Creek Headwaters 110
20 km
Mumm Creek 177
Burrows
Basin
Facies
Formation
East D'
ructures
Thoroughly Churned
Mottled
Root Casts
Tubular Inclined
Sedimentary Structures
Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Load Casts
Ibrication
Tabular-planar Cross-stratification
High Angle Cross-stratification
Ripple Stratification (Wave)
Soft Sediment Deformation
Flaser-bedding
Scour and Fill
Minor Faulting
Organic Remains
Carbonaceous Matter
Bones
Coal Chips
Fish Debris
Phosphate Pellets or Oolites
Phosphate Pebbles
Transported Wood
Invertebrate Fossils
Belemnites
Phosphate Nodules
Phosphatic (>1% P₂O₅)
Cement and Accessory Minerals
Glauconite
Bentonite
Iron Oxide Cement
Ironstone Concretions
Pyrite
Calcareous
Sideritic Cement
Dolomitic
Phosphate Cement
Sharp
Erosional and Unconformable
Gradational
Obscured Contact

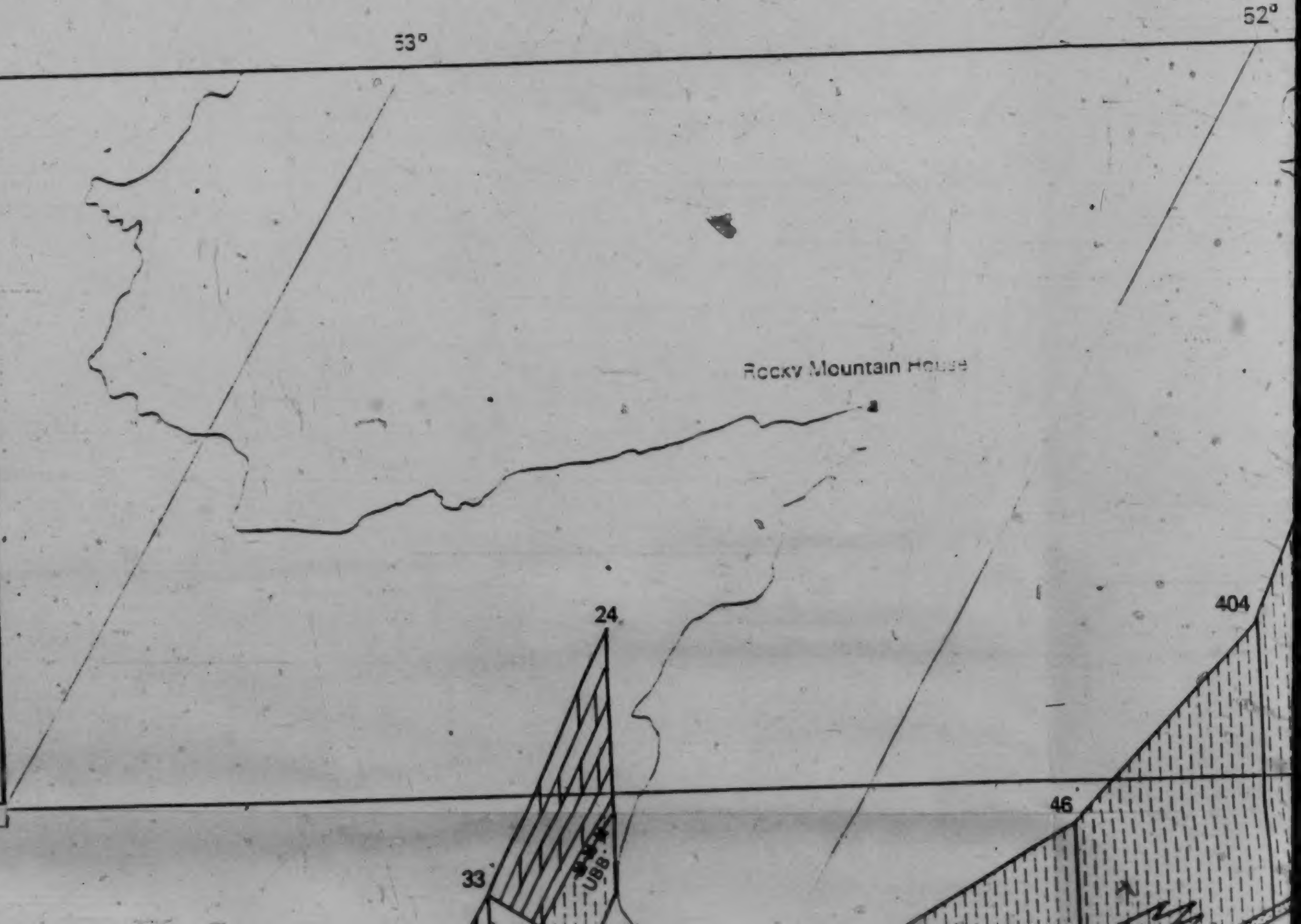

North Saskatchewan
Red Deer River
Bow River
Calgary
53°
52°
51°
49°
114°
116°
D
C
C'
B
B'
E'
A'
Scale 1:3,000,000
Present Location of Section
Palinspastically Restored Position of Section
0 25 50 km

6oF6

1 of



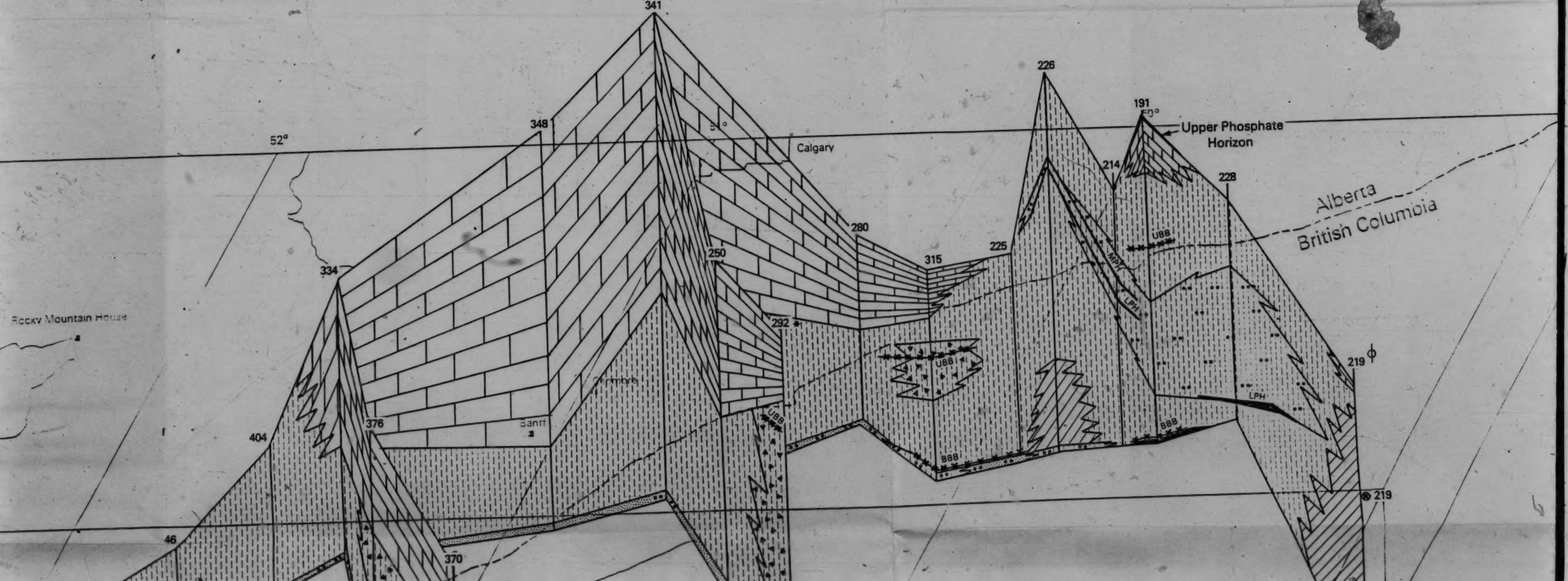
Scale 1:3,000,000
Present Location of Section
Palinspastically Restored Position of Section
0 25 50 km
N
Calgary
North Saskatchewan River
Red Deer River
Bow River
Athabasca River
54°
53°
52°
51°
49°
114°
118°

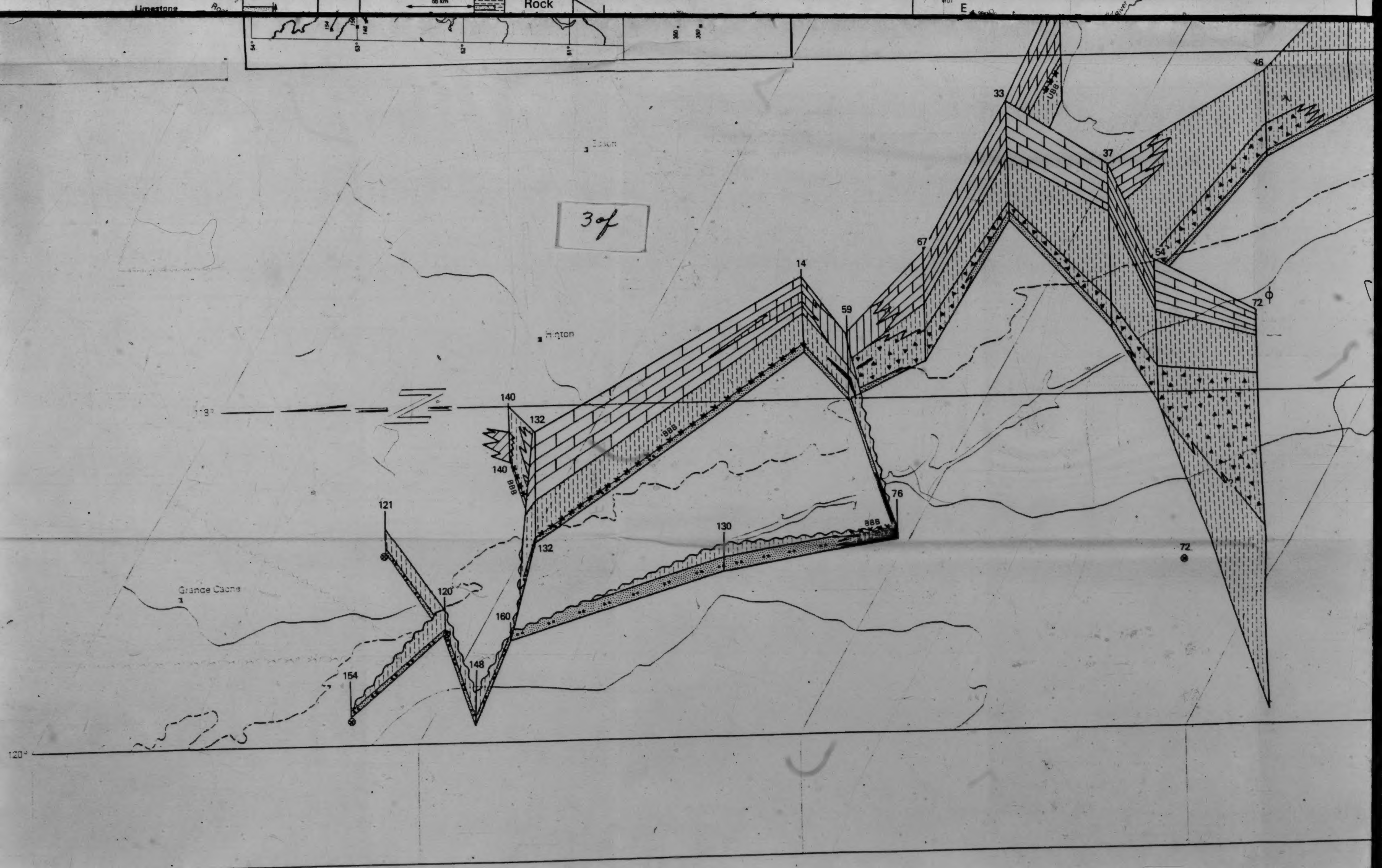


53°
52°
Rocky Mountain House
24
404
46
33
UBB

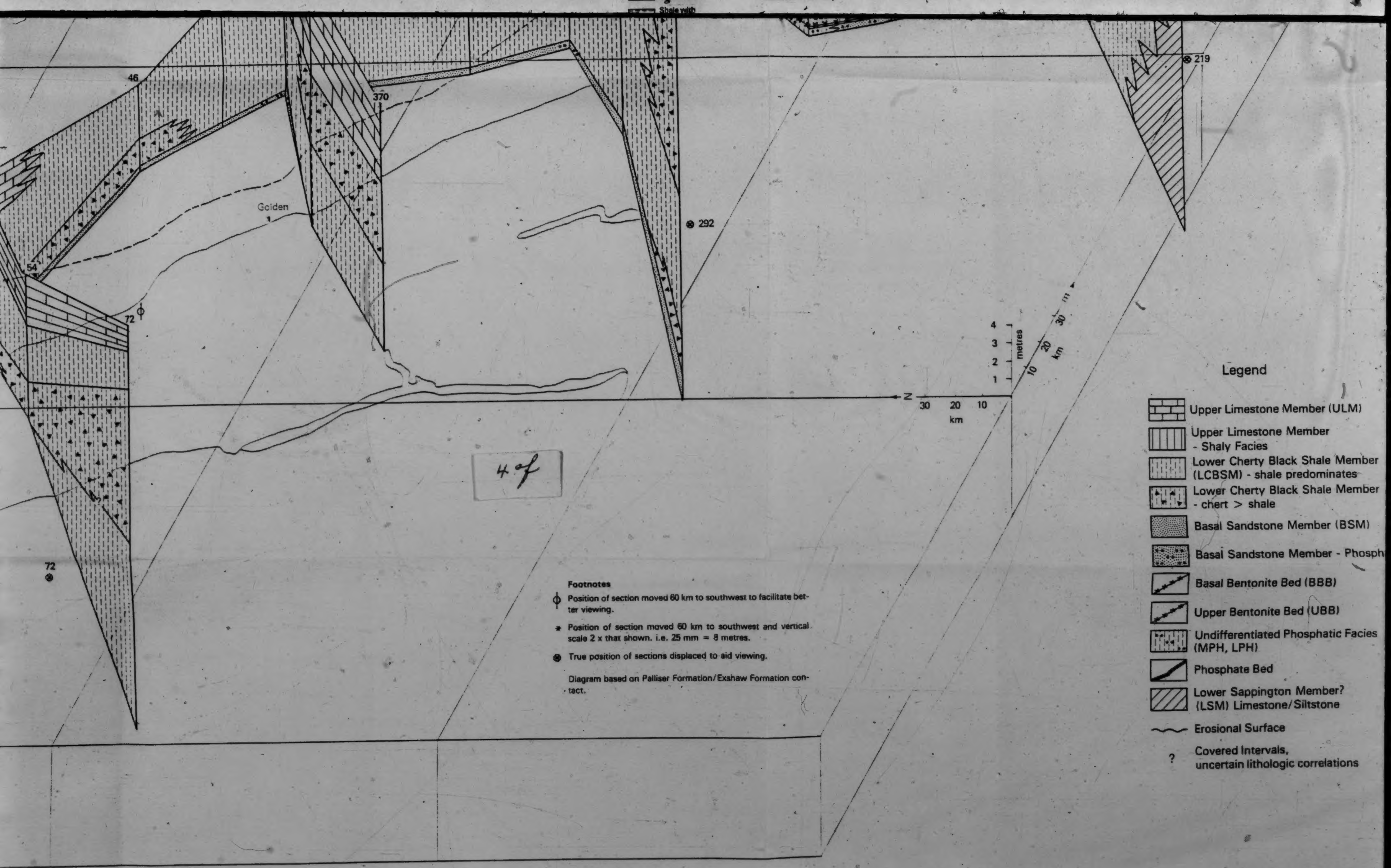
Summit
Limestone
Mountain
Rock

2 of


341
348
52°
51°
Calgary
226
191
50°
Upper Phosphate Horizon
214
228
Alberta
British Columbia
280
315
225
250
334
292
UBB
MPH
LPH
Rocky Mountain House
Canmore
Banff
376
404
BBB
219
46
370


Limestone
Rock
E
54°
53°
52°
51°
154
148
Edson
Hinton
118°
Grande Cache
120°
140
132
14
59
67
33
37
46
54
72
UBB
BBB
121
120
160
148
154
130
76
72

3 of



4 of

Legend

- ▦ Upper Limestone Member (ULM)
- ▥ Upper Limestone Member - Shaly Facies
- ▨ Lower Cherty Black Shale Member (LCBSM) - shale predominates
- ▨ Lower Cherty Black Shale Member - chert > shale
- ▒ Basal Sandstone Member (BSM)
- ▒ Basal Sandstone Member - Phosph
- ▨ Basal Bentonite Bed (BBB)
- ▨ Upper Bentonite Bed (UBB)
- ▨ Undifferentiated Phosphatic Facies (MPH, LPH)
- ▨ Phosphate Bed
- ▨ Lower Sappington Member? (LSM) Limestone/Siltstone
- 〜 Erosional Surface
- ? Covered Intervals, uncertain lithologic correlations

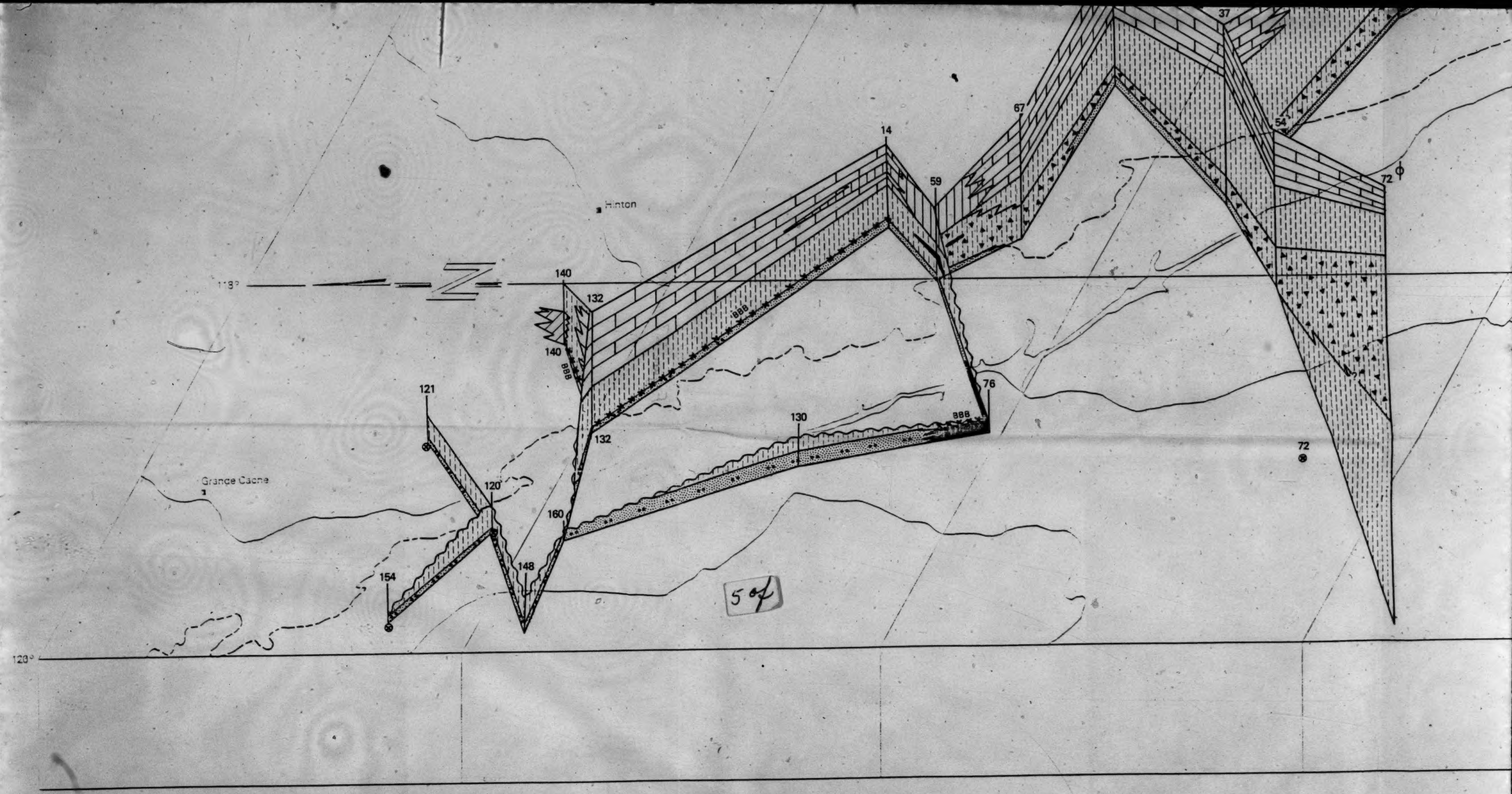
Footnotes

ϕ Position of section moved 60 km to southwest to facilitate better viewing.

* Position of section moved 60 km to southwest and vertical scale 2 x that shown. i.e. 25 mm = 8 metres.

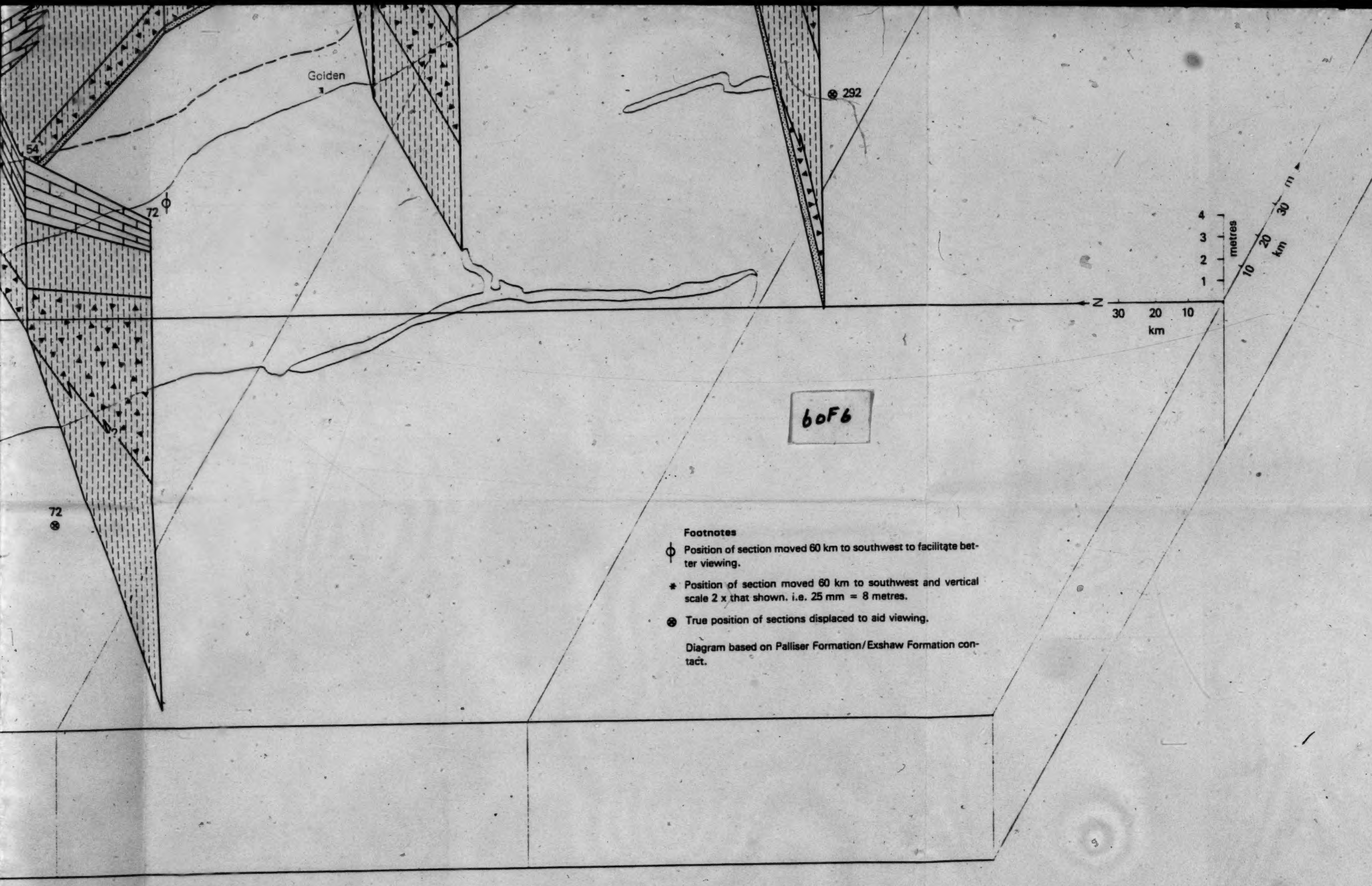
⊗ True position of sections displaced to aid viewing.

Diagram based on Palliser Formation/Exshaw Formation contact.


37
67
14
59
54
72
Hinton
118°
140
132
140
BBB
BBB
121
76
130
BBB
132
72
Grande Cache
120
160
148
154
120°

5 of

Figure 27. Fence diagram illustrating correlation of Exshaw Formations units — Palinspastically restored and location of stratigraphic sections studied



60F6

Footnotes

ϕ Position of section moved 60 km to southwest to facilitate better viewing.

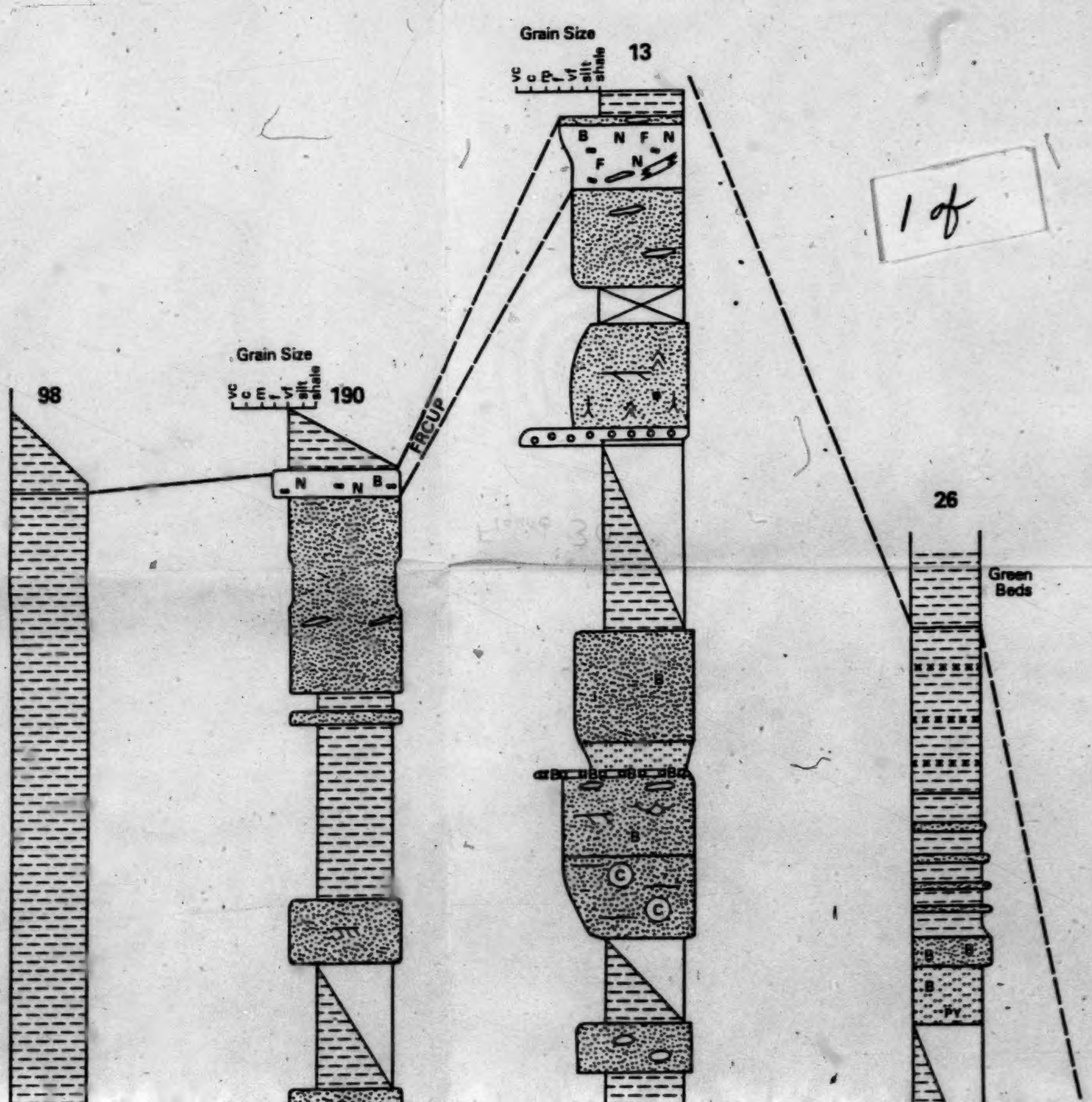
* Position of section moved 60 km to southwest and vertical scale 2 x that shown, i.e. 25 mm = 8 metres.

⊗ True position of sections displaced to aid viewing.

Diagram based on Palliser Formation/Exshaw Formation contact.

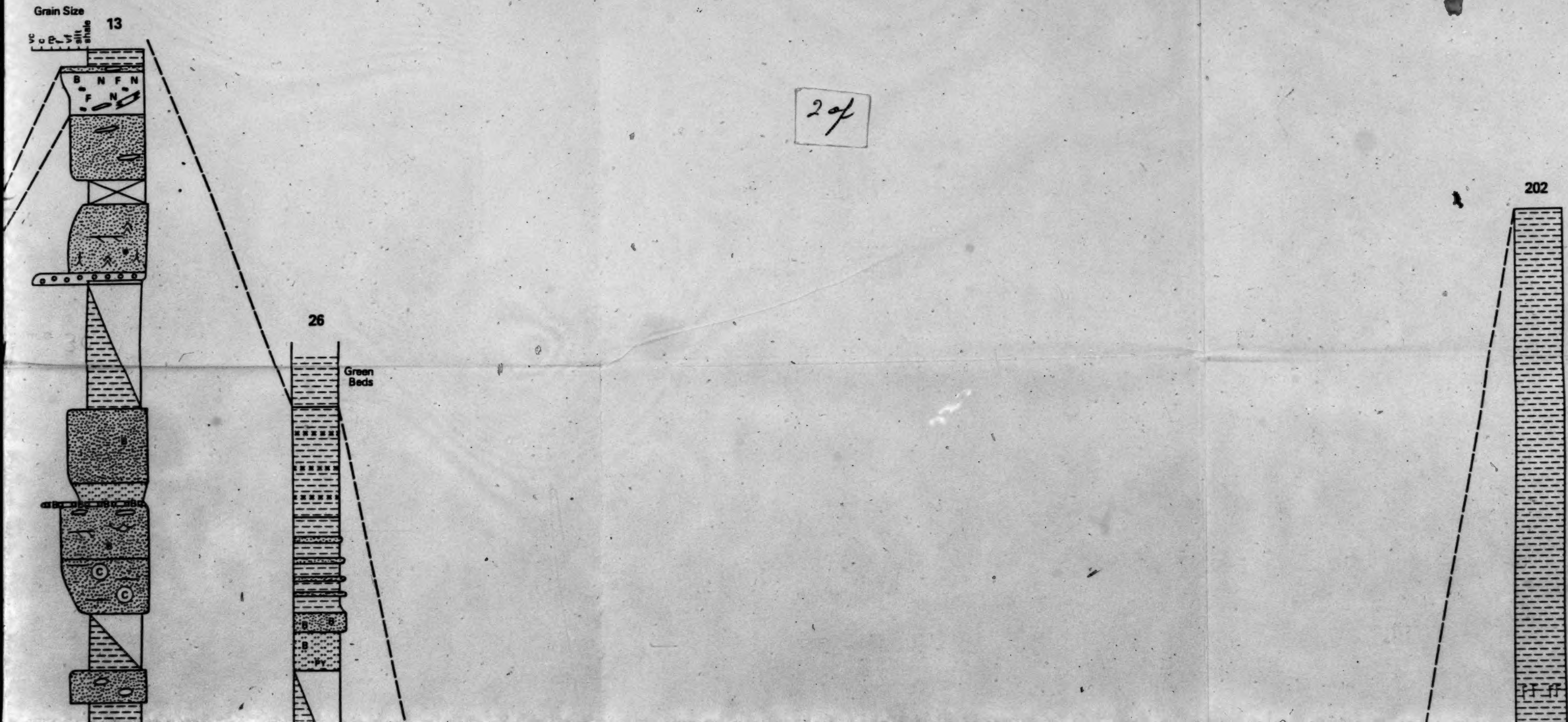
Legend

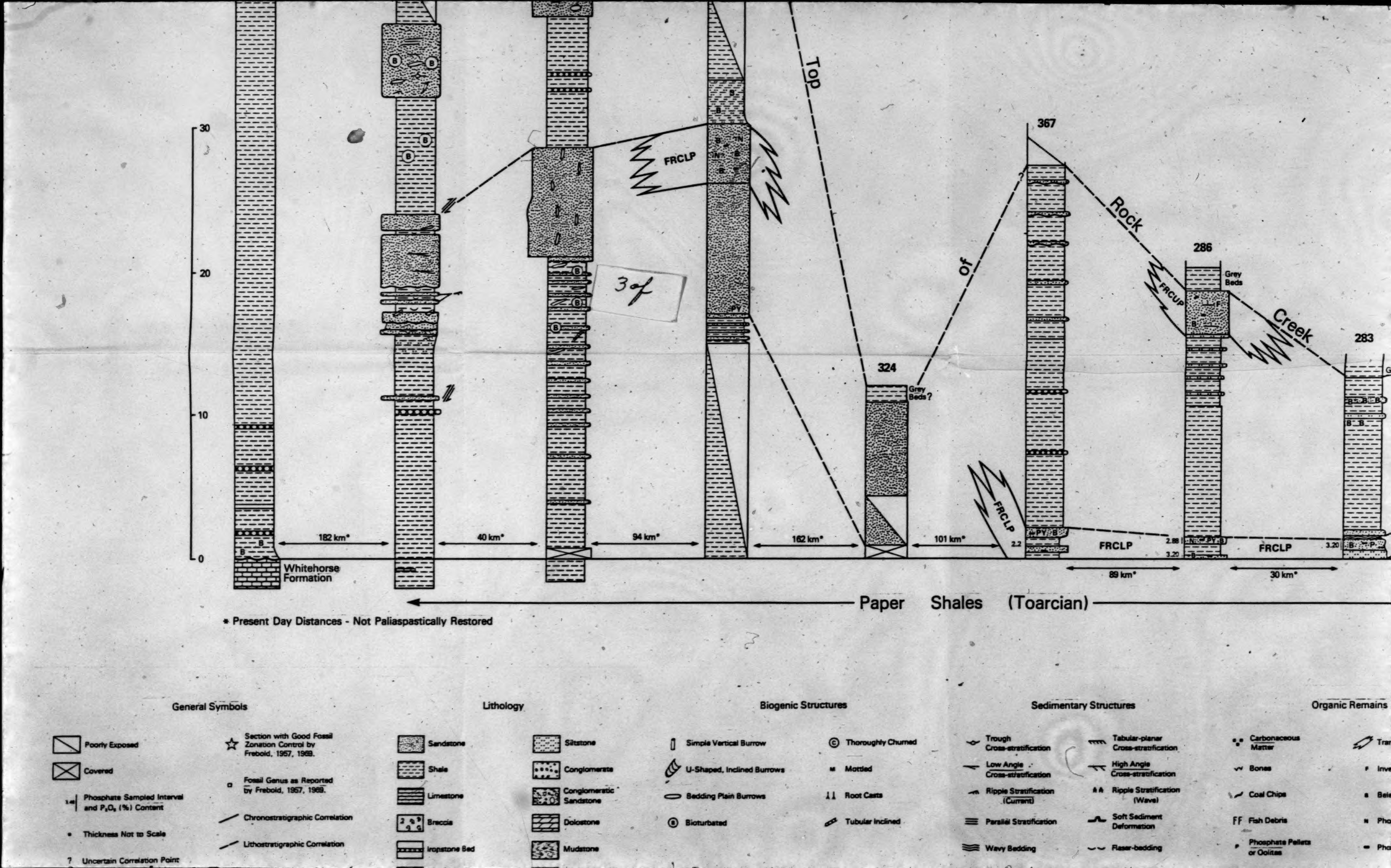
- ▦ Upper Limestone Member (ULM)
- ▥ Upper Limestone Member - Shaly Facies
- ▤ Lower Cherty Black Shale Member (LCBSM) - shale predominates
- ▨ Lower Cherty Black Shale Member - chert > shale
- ▩ Basal Sandstone Member (BSM)
- ▩ Basal Sandstone Member - Phosphate
- ▧ Basal Bentonite Bed (BBB)
- ▧ Upper Bentonite Bed (UBB)
- ▨ Undifferentiated Phosphatic Facies (MPH, LPH)
- ▧ Phosphate Bed
- ▧ Lower Sappington Member? (LSM) Limestone/Siltstone
- 〰 Erosional Surface
- ? Covered Intervals, uncertain lithologic correlations


Grain Size
vc c m f vf silt shale
13
B N F N
F N
Grain Size
vc c m f vf silt shale
190
98
N N B
FRCUP
26
Green Beds
B B
B
Py

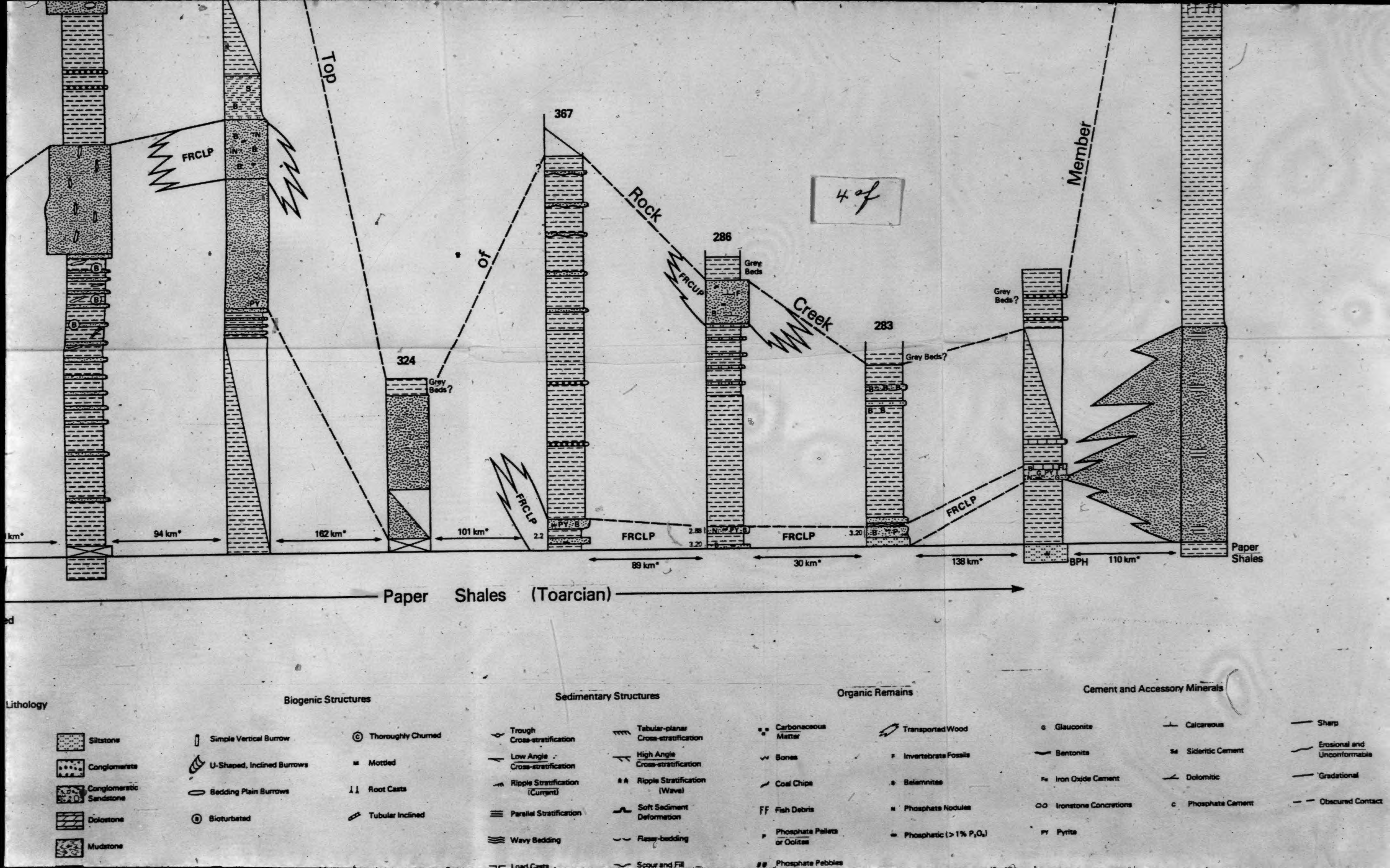
1 of

2 of

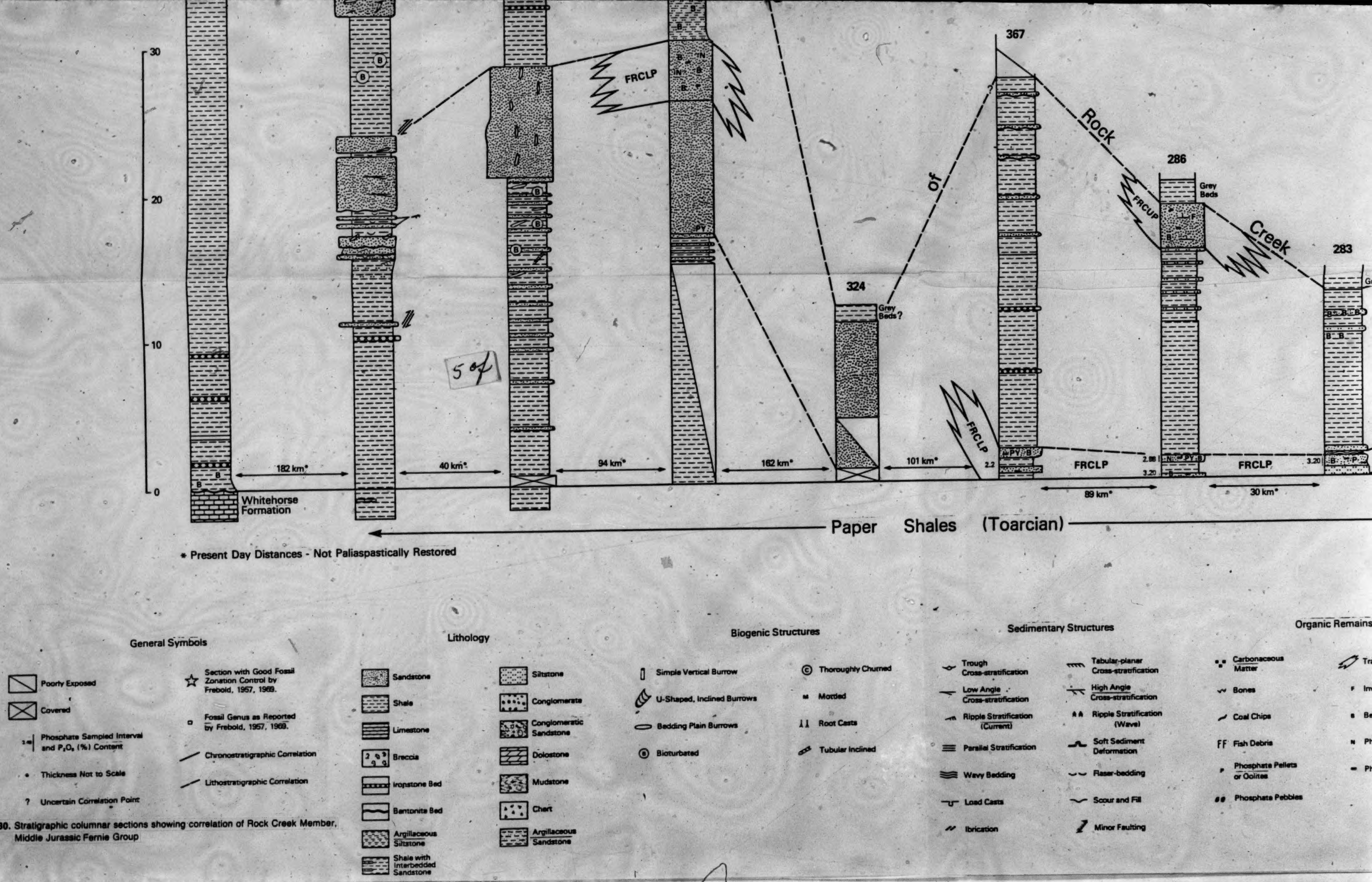

Grain Size
vc
c
m
f
vf
silt
shale
13
B
N
F
N
F
N
B
C
C
26
Green Beds
B
B
B
Py
202


Top
of
Rock
Creek
30
20
10
0
FRCLP
FRCUP
324
Grey Beds?
367
286
Grey Beds
283
B
N
PY
F
P
2.2
2.88
3.20
3.20
182 km*
40 km*
94 km*
162 km*
101 km*
89 km*
30 km*
Whitehorse Formation
Paper Shales (Toarcian)
* Present Day Distances - Not Paliaspastically Restored
General Symbols
Poorly Exposed
Covered
Phosphate Sampled Interval and P_2O_5 (%) Content
Thickness Not to Scale
Uncertain Correlation Point
Section with Good Fossil Zonation Control by Frebold, 1957, 1969.
Fossil Genus as Reported by Frebold, 1957, 1969.
Chronostratigraphic Correlation
Lithostratigraphic Correlation
Lithology
Sandstone
Shale
Limestone
Breccia
Ironstone Bed
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Biogenic Structures
Simple Vertical Burrow
U-Shaped, Inclined Burrows
Bedding Plain Burrows
Bioturbated
Thoroughly Churned
Mottled
Root Casts
Tubular Inclined
Sedimentary Structures
Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Tabular-planar Cross-stratification
High Angle Cross-stratification
Ripple Stratification (Wave)
Soft Sediment Deformation
Flaser-bedding
Organic Remains
Carbonaceous Matter
Bones
Coal Chips
Fish Debris
Phosphate Pellets or Oolites
Tra
Inve
Bele
Pho
Pho

3of


Top
of
Rock
Creek
Member
FRCLP
FRCUP
367
324
286
283
Grey Beds
Grey Beds?
2.2
2.88
3.20
3.20
BPH
km*
94 km*
162 km*
101 km*
89 km*
30 km*
138 km*
110 km*
Paper Shales
Paper Shales (Toarcian)
ed
Lithology
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Biogenic Structures
Simple Vertical Burrow
U-Shaped, Inclined Burrows
Bedding Plain Burrows
Bioturbated
Thoroughly Churned
Mottled
Root Casts
Tubular Inclined
Sedimentary Structures
Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Load Casts
Tabular-planar Cross-stratification
High Angle Cross-stratification
Ripple Stratification (Wave)
Soft Sediment Deformation
Flaser-bedding
Scour and Fill
Organic Remains
Carbonaceous Matter
Bones
Coal Chips
Fish Debris
Phosphate Pellets or Oolites
Phosphate Pebbles
Transported Wood
Invertebrate Fossils
Belemnites
Phosphate Nodules
Phosphatic (> 1% P2O5)
Cement and Accessory Minerals
Glauconite
Bentonite
Iron Oxide Cement
Ironstone Concretions
Pyrite
Calcareous
Sideritic Cement
Dolomitic
Phosphate Cement
Sharp
Erosional and Unconformable
Gradational
Obscured Contact

4 of



30
20
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0
Whitehorse Formation
182 km*
40 km*
94 km*
162 km*
101 km*
89 km*
30 km*
FRCLP
FRCUP
Rock of Creek
324
Grey Beds?
367
286
Grey Beds
283
2.2
2.88
3.20
3.20
PY
B
N
F
5 of
Paper Shales (Toarcian)
* Present Day Distances - Not Paliaspastically Restored
General Symbols
Poorly Exposed
Covered
Phosphate Sampled Interval and P₂O₅ (%) Content
Thickness Not to Scale
? Uncertain Correlation Point
Section with Good Fossil Zonation Control by Frebold, 1957, 1969.
Fossil Genus as Reported by Frebold, 1957, 1969.
Chronostratigraphic Correlation
Lithostratigraphic Correlation
Lithology
Sandstone
Shale
Limestone
Breccia
Ironstone Bed
Bentonite Bed
Argillaceous Siltstone
Shale with Interbedded Sandstone
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Chert
Argillaceous Sandstone
Biogenic Structures
Simple Vertical Burrow
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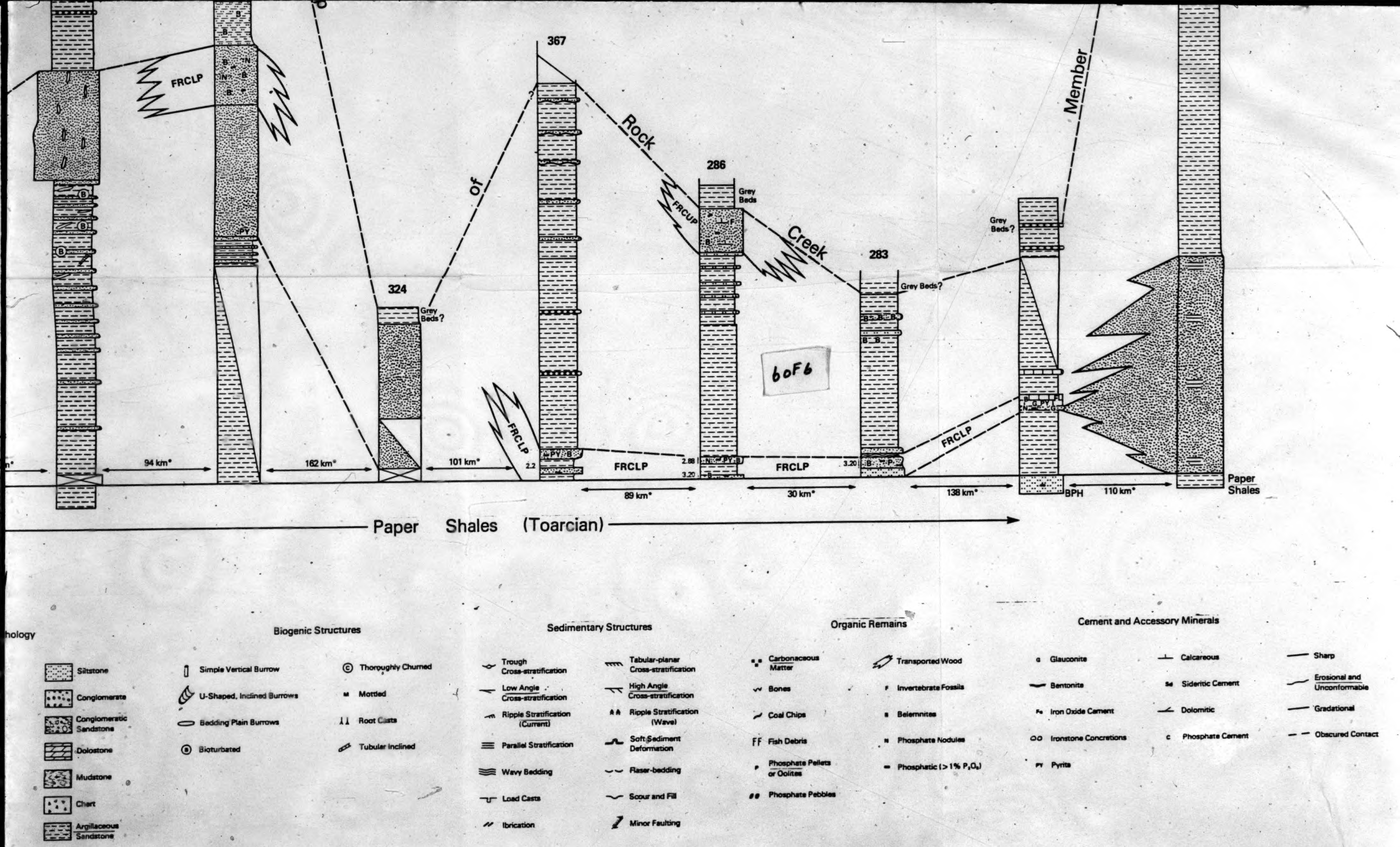
Parallel Stratification
Wavy Bedding
Load Casts
Ibrication
Tabular-planar Cross-stratification
High Angle Cross-stratification
Ripple Stratification (Wave)
Soft Sediment Deformation
Flaser-bedding
Scour and Fill
Minor Faulting
Organic Remains
Carbonaceous Matter
Bones
Coal Chips
Fish Debris
Phosphate Pellets or Oolites
Phosphate Pebbles

Figure 30. Stratigraphic columnar sections showing correlation of Rock Creek Member, Middle Jurassic Fernie Group


FRCLP
367
324
Grey Beds?
of
Rock
Creek
Member
286
Grey Beds
FRCUP
283
Grey Beds?
FRCLP
PY
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N
F
G
94 km*
162 km*
101 km*
2.2
FRCLP
2.88
3.20
89 km*
FRCLP
30 km*
3.20
138 km*
BPH
110 km*
Paper Shales
Paper Shales (Toarcian)
hology
Siltstone
Conglomerate
Conglomeratic Sandstone
Dolostone
Mudstone
Chert
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Simple Vertical Burrow
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Root Casts
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Trough Cross-stratification
Low Angle Cross-stratification
Ripple Stratification (Current)
Parallel Stratification
Wavy Bedding
Load Casts
Ibrication
Tabular-planar Cross-stratification
High Angle Cross-stratification
Ripple Stratification (Wave)
Soft Sediment Deformation
Flaser-bedding
Scour and Fill
Minor Faulting
Organic Remains
Carbonaceous Matter
Bones
Coal Chips
Fish Debris
Phosphate Pellets or Oolites
Phosphate Pebbles
Transported Wood
Invertebrate Fossils
Belemnites
Phosphate Nodules
Phosphatic (> 1% P₂O₅)
Cement and Accessory Minerals
Glauconite
Bentonite
Iron Oxide Cement
Ironstone Concretions
Pyrite
Calcareous
Sideritic Cement
Dolomitic
Phosphate Cement
Sharp
Erosional and Unconformable
Gradational
Obscured Contact

6oF6